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POLARIZATION FIGURES AND ROTATION PROPERTIES IN REFLECTED LIGHT AND THEIR APPLICATION TO THE IDENTIFICATION OF ORE MINERALS.

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ABSTRACT.

Polarization figures given by opaque minerals in convergent reflected light are described, and an explanation of the figures is offered. Three properties of isotropic opaque minerals determinable from polarization figures are defined: the strength of dispersion of the reflection rotation, the relative dispersion of the reflection rotation, and the dispersion of the ellipticity. These properties are related to the rotation of the vibration planes of incident convergent plane-polarized rays by reflection from polished surfaces or crystal faces of isotropic minerals. Isotropic minerals differ in dispersion properties; hence the properties can be used as an aid in identification.

Six properties of anisotropic minerals determinable from their polarization figures are defined: the sense of rotation of incident plane-polarized light with respect to known crystallographic elements, the degree of dispersion of the reflection rotation, the relative dispersion of the reflection rotation, the apparent angle of rotation due to anisotropy of the mineral, the amount of dispersion of the apparent angle of rotation, and the relative dispersion of the apparent angle of rotation. Opaque anisotropic minerals differ in their rotation properties; the properties can therefore be used for distinguishing them.

Procedures for analysis of polarization figures are described and the results of observations of polarization figures for a group of about 40 isotropic and anisotropic opaque minerals are given. The technique appears to offer material aid in the identification of ore minerals, the more so because analysis of polarization figures is quickly and readily done.

INTRODUCTION.

In 1947 and 1948, optical figures obtained by conoscopic observation of minerals in reflected light were discussed in two interesting articles by G. J. Neuerburg.[1] Two principal types of figures were described and illustrated.

[1] Neuerburg, G. J., Optical figures obtained with the reflecting microscope: Am. Mineralogist, vol. 32, pp. 527–543, 1947. Effects of rotation of objectives on the optical properties of opaque minerals in polarized light: Am. Mineralogist, vol. 33, pp. 496–502, 1948.

One is a dark cross resembling the interference figure given by a basal section of a uniaxial mineral in transmitted light. The other is similar to the acute bisectrix interference figure given by a biaxial mineral of low birefringence. The first type of figure remains unchanged as the stage is rotated. The second type is cruciform at four positions of the stage 90 degrees apart, but at intermediate positions the cross breaks into two isogyres occupying opposite quadrants of the field. The figures are striking phenomena, but their meaning and usefulness in the study of ore minerals have remained in doubt owing to lack of an explanation.

During recent months, a study in progress at the University of Wisconsin has led to an explanation of the figures and has shown that they afford a set of optical properties that can be used in identification of ore minerals. The figures are here designated polarization figures. They offer a delicate test for the distinction of isotropic from anisotropic minerals. Figures given by isotropic minerals furnish information on dispersion characteristics; figures given by anisotropic minerals yield information on dispersion characteristics and on other properties as well. The properties of anisotropic minerals thus far recognized are (1) the strength of dispersion of the reflection rotation, (2) the relative dispersion of the reflection rotation, (3) the apparent angle of rotation of the vibration plane of incident plane-polarized light, (4) the magnitude of dispersion of the apparent rotation of the vibration plane, (5) the relative dispersion (red relative to blue) of the apparent angle of rotation, and (6) the positive or negative sense of rotation of the vibration plane with respect to known crystallographic elements. These properties are characteristic for each of the species of anisotropic minerals. They can be studied with a standard type of mineragraphic microscope in approximately the amount of time required for obtaining and analyzing an interference figure of an anisotropic mineral in transmitted light. The apparent rotation and the magnitude of the dispersion of the apparent rotation are quantities that can be measured with considerable precision for minerals of moderate to high rotation and dispersion. The full potentialities of the figures are yet to be explored. It is already clear, however, that they will be of considerable assistance in the identification of ore minerals and that they are a useful addition to the group of optical properties —color, bireflection, anisotropism, etc.—that have customarily been used in the recognition of ore minerals in reflected light.

POLARIZATION FIGURES.

General Statement.—Discussion of the polarization figures given by absorbing ("opaque") minerals in reflected light is greatly facilitated by considering first the explanation of similar figures obtained from dielectric (transparent) minerals in reflected light. This scheme of presentation is therefore adopted in the sections that follow. The figures produced by isotropic minerals are examined and their behavior analyzed. The figures given by anisotropic minerals are then discussed.

Polarization Figures of Transparent Isotropic Minerals.—Plane-polarized rays perpendicularly incident upon a polished surface of an isotropic transparent

mineral are reflected without change either of phase or of azimuth of vibration.[2] If a low-power objective is used in microscopic examination of the surface in polarized light, perpendicular incidence of the rays over the field is almost fully achieved. Between crossed nicols, the section therefore remains dark during a 360° rotation of the stage. If a high-power objective is used, however, the light passing downward [3] through the objective is refracted and converges strongly to its field of incidence upon the specimen. If the vibration plane of the polarizer is north-south, rays incident along the north-south diameter of the field after refraction have vibration directions lying within the plane of incidence of the rays. These rays undergo neither phase change nor change of azimuth of vibration upon reflection; hence they are extinguished in the analyzer. Rays incident along the east-west diameter of the field after refraction in the objective have vibration directions that are perpendicular to their plane of incidence. The azimuths of vibration of these rays are unchanged by reflection from the polished surface. They likewise are extinguished in the analyzer. In all other portions of the field, the refracted rays passing from the objective toward the polished surface have azimuths of vibration that lie neither within nor perpendicular to the planes of incidence of the rays. The geometric relationships involved are complex but may be expressed graphically as in Figure 1. In the figure, the vibration directions of the rays incident along the north-south and east-west diameters of the field are shown by double-headed arrows. The azimuths of vibration of the rays incident upon the polished surface in the remainder of the field are shown by solid lines, the azimuths of vibration of the corresponding reflected rays by dashed lines. The figure shows that away from the principal diameters of the field the general effect of refraction and convergence is a rotation of the planes of vibration of the incident rays. As shown in the figure this rotation increases systematically away from the optical center of the field and likewise away from the north-south and east-west diameters. The rotation is symmetrical with respect to the vibration plane of the polarizer.

The rotation due to convergence and refraction is matched by an equal and opposite rotation that takes place as the rays pass back from the polished surface through the objective; it is therefore significant only to the extent that it influences the pattern of the azimuths of vibration of the rays incident over the field of the microscope. Much more important is the rotation of the azimuths of vibration produced by reflection of the rays at the surface of the mineral. This rotation takes place because the components of the incident vibration parallel and perpendicular to the plane of incidence are not reflected with equal amplitude. The results are shown graphically in Figure 2 [4] for a ray incident in the northeast quadrant of the field. The amount of rotation increases with the angle of incidence and with the divergence of the plane of vibration from the plane of incidence of the ray. The rotation is clockwise for rays incident in the northwest and southeast quadrants of the field (Fig. 1), counterclockwise

[2] By "azimuth of vibration" is meant the horizontal angle between the vibration plane of the ray and a given reference plane, usually the plane of incidence of the ray.

[3] In the following, it is assumed that the microscope is of the normal upright type.

[4] Reflection also causes a phase change of 180° in that component of the reflected vibration that is perpendicular to the plane of incidence. This change is embodied in Figure 2.

for rays incident in the northeast and southwest quadrants; it is therefore symmetrical with respect to the plane of vibration of light from the polarizer. If now the analyzer is introduced and the ocular removed or a Bertrand lens inserted into the system, a cruciform figure resembling the interference figure given by a basal section of a uniaxial mineral in transmitted light is seen (Fig.

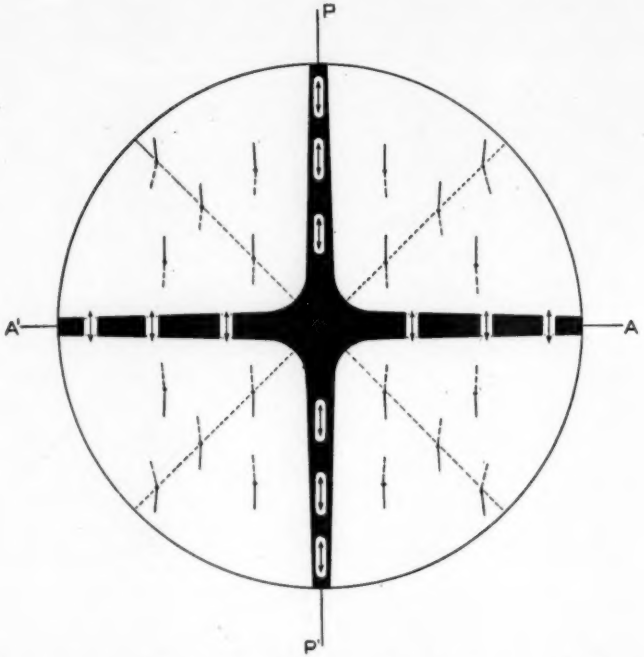

FIG. 1. Diagram showing the polarization figure of an isotropic mineral and the relation of the figure to the azimuths of vibration of incident and reflected plane-polarized rays. Polarizer (PP') and analyzer (A'A) exactly crossed. Double-headed arrows show vibration azimuths of both incident and reflected rays for points along the north-south and east-west diameters of the field. In the quadrants between the arms of the cross (black) vibration directions of incident rays are shown by solid lines, vibration directions of reflected rays by dashed lines. Monochromatic light,

1). The arms of the cross are formed along the N-S and E-W diameters of the field, where the vibration planes of the incident rays are not rotated. The remainder of the field, where the vibration planes of the reflected rays lie at various angles to the vibration plane of the polarizer, is illuminated.

The foregoing explanation is qualitative and is furthermore incomplete in that it makes no allowance for a very slight further rotation during passage of

the reflected rays back through the reflecting unit, which in the case presented is a coated glass plate. Full treatment of these effects would require a complex mathematical analysis, but this is unnecessary to an understanding of the figures. The additional rotation does not affect the validity of the measurements of the optical characteristics of minerals treated in later sections. The qualitative validity of the explanation given here may be verified quite simply. If the analyzer is rotated clockwise from the crossed position, the dark cross separates into two isogyres that move outward into the northwest and south-

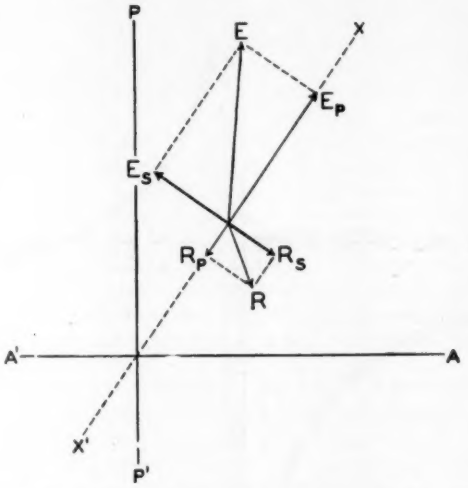

FIG. 2. Diagram showing resolution and reflection of a plane-polarized ray incident at a point in the northeast quadrant of the field of view. E, azimuth of vibration of the incident ray; E_p, component of E parallel to the plane of incidence (XX') of the ray; E_s, component of E perpendicular to the plane of incidence; R, azimuth of vibration of the reflected ray; R_p, component of R parallel to the plane of incidence; R_s, component of R perpendicular to the plane of incidence. PP', plane of polarizer; A'A, plane of analyzer. Monochromatic light. Components of the incident ray drawn looking along the direction of propagation of the ray; components of the reflected ray drawn looking against the direction of propagation of the ray.

east quadrants as the rotation of the nicol is increased. Counterclockwise rotation produces isogyres that move into the northeast and southwest quadrants. As indicated in Figure 3, for any given position of the nicol the isogyres must be assemblages of points for which the vibration directions of reflected rays reaching the analyzer are perpendicular to the rotated plane of vibration of the nicol. The movement of the isogyres shows that the divergence of the azimuths of vibration of the reflected rays from the plane of the polarizer increases outward from the center of the field and away from the N-S and E-W

diameters, reaching a maximum at the periphery of the field along the NW-SE and NE-SW diameters.

Polarization Figures of Isotropic, Absorbing Crystals.—The essential optical difference between transparent minerals and "opaque minerals" such as the sulphides and other ordinary ore minerals is that the "opaque minerals" absorb part of the light that is incident upon them. Absorption is related to electrical properties. Absorbing power rises in general with electrical conductivity and

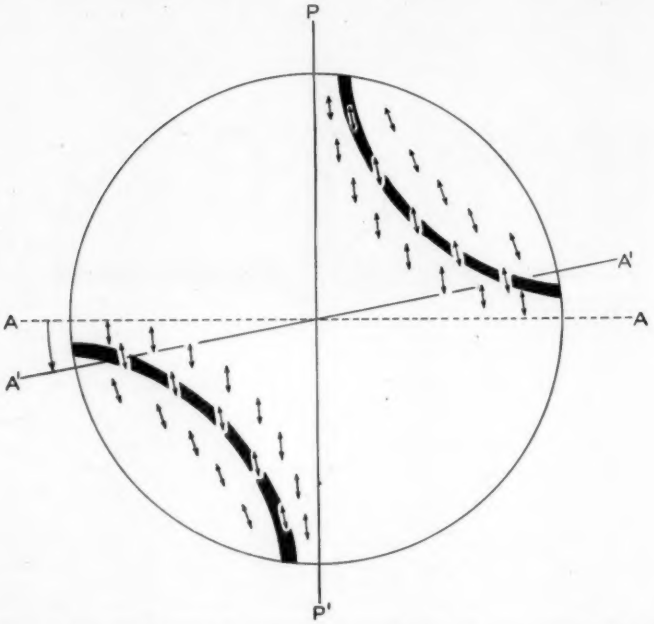

FIG. 3. Diagram showing relation of appearance and movement of isogyres, produced in the polarization figure of an isotropic mineral by rotation of the analyzer, to vibration directions of rays reflected from the surface of the mineral. Double-headed arrows show vibration directions of the reflected rays. PP', plane of polarizer; AA, plane of analyzer prior to rotation; A'A', present rotated position of analyzer. Monochromatic light.

reaches a maximum for those metals that have highest conductivity.[5] The polarization figures given by isotropic "opaque minerals" are similar to those produced by isotropic transparent minerals but owing to absorption are produced in a somewhat different way. Plane-polarized light perpendicularly incident on a polished surface of an absorbing isotropic mineral is reflected back

[5] Jenkins, F. A., and White, H. E., Fundamentals of Physical Optics, 1st edit., pp. 397–418, McGraw-Hill Book Co., New York, 1937.

as plane-polarized light without rotation of the plane of vibration. Light obliquely incident with its vibration plane perpendicular or parallel to its plane of incidence is likewise reflected as linearly polarized light with its azimuth of vibration unchanged. Under conoscopic conditions, therefore, the E-W and N-S diameters of the field of the microscope are again loci of extinction. All the other rays, however, are obliquely incident on the field with vibration planes neither parallel nor perpendicular to their planes of incidence. Each ray is resolved upon reflection into two components, one parallel and one perpendicular to the plane of incidence of the ray. These components acquire a phase difference which is less than 180°; hence in general they produce a ray that is elliptically polarized. This elliptical vibration is resolved in the analyzer into a plane-polarized ray; the plane of vibration of the ray is rotated with respect to the plane of vibration of the incident ray and is divergent likewise from the plane of vibration that would result if the reflecting surface were a surface of a transparent mineral. The ellipticity of the reflected vibration increases with the absorbing power of the mineral. The divergence of the plane of vibration of the plane-polarized ray produced from this elliptical vibration in the analyzer from that of the ray that would be produced if there were no absorption likewise increases with the absorbing power of the mineral. Most isotropic ore minerals, however, have low absorption and give polarization figures that do not differ essentially from those of transparent isotropic minerals. Minerals of high conductivity are chiefly certain native metals such as gold, copper, and silver. Their strong absorptions probably explain the narrowness of the band of complete extinction along the east-west and north-south diameters of the field.

Effects of Rotation of the Analyzer.—The effects of rotation of the analyzer on polarization figures vary with the light used and with the mineral species under observation. In monochromatic light, all figures of isotropic absorbing minerals show separation of the cross into two isogyres resembling those of an acute bisectrix figure in transmitted light. If white light is used, isogyres of the figures of some absorbing minerals are black and sharply defined, but figures of other minerals show one of two types of color patterns. One type is illustrated by the polarization figure of pyrite when the analyzer is rotated (Fig. 4A). The midlines of the isogyres are sensibly black throughout their length, but there is a bluish fringe on the concave side of each isogyre and a reddish fringe on the convex side, as shown in the figure. The second type of color pattern is illustrated by the polarization figure of gold when the analyzer is rotated (Fig. 4B). The two isogyres are black at their ends, but in the vicinity of the diagonal of the field that intersects their midportions the black is replaced by a golden-yellow hue.

Color variations of the type shown by pyrite have their origin in dispersion of the rotation produced by reflection at the surface of the mineral. It will be recalled that light incident in the four quadrants of the field is reflected back as elliptically polarized rays. At any given point in one of the quadrants, the azimuth of the vibration ellipse is not only a function of the angle of incidence of the ray and its azimuth of vibration with respect to the plane of incidence,

but is also a function of the indices of refraction and absorption of the reflecting mineral. These indices differ for various wavelengths of light, either increasing or decreasing with the wavelength. The azimuth of the ray reflected from any given point in one of the quadrants will therefore not be the same for all wavelengths of light. This divergence, which is a dispersion of the reflection rotation, will increase in general outward from the center of the field and away from the north-south and east-west diameters (i.e., the diameters respectively parallel and perpendicular to the vibration plane of the polarizer). If the dispersion of the azimuth of rotation is small, no effect will be seen, but if the dispersion is marked, then at points well away from the center of the field and the two principal diameters simultaneous extinction of all wavelengths of light by rotation of the analyzer is impossible, and color fringes will appear on the isogyres.

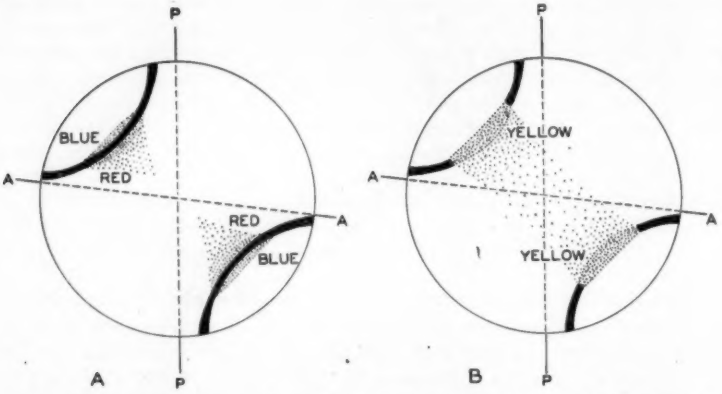

FIG. 4. Polarization figures of pyrite (A) and gold (B) after clockwise rotation of the analyzer. PP′, plane of polarizer; A′A, plane of analyzer. White light.

A red color fringe on an isogyre indicates that at the position of the fringe the effective vibration directions for blue light are parallel to the vibration plane of the analyzer, so that blue light is extinguished by the analyzer. Similarly, a blue fringe is the assemblage of points at which vibration directions for red are parallel to that of the analyzer. The relations for pyrite are as shown in Fig. 5. If we recall that the rotation of the azimuth of vibration of convergent plane-polarized rays increases with increase in the angle of incidence, then it is evident that for the mineral in the figure a greater angle of incidence is required for rotation of red light to the azimuth required for extinction than is required for rotation of blue light. This can only mean that the rotational effect of the mineral is greater for blue than for red. This property is here designated the *dispersion of the reflection rotation*. The symbol suggested for this property is DR_r and the notation suggested for the case of pyrite is $DR_r = v > r$. The reverse disposition of the fringes would indicate $DR_r = r > v$.

Color variations of the type shown by the polarization figure of gold are believed to have their origin in dispersion of the ellipticity produced by reflection of light at the surface of the mineral. When plane-polarized light incident on a mineral section becomes elliptically polarized, a phase shift as well as a rotation of the plane of vibration is introduced. If an elliptically polarized ray is examined with a nicol prism, no true extinction results at any position as the nicol is rotated through 360°. Instead there are two positions of maximum brightness 180° apart alternating with two positions of maximum darkness 180° apart. Maximum brightness occurs when the vibration plane of the prism is parallel to the major axis of the vibration ellipse; maximum darkness occurs when the plane of the nicol is parallel to the minor axis of the vibration ellipse.

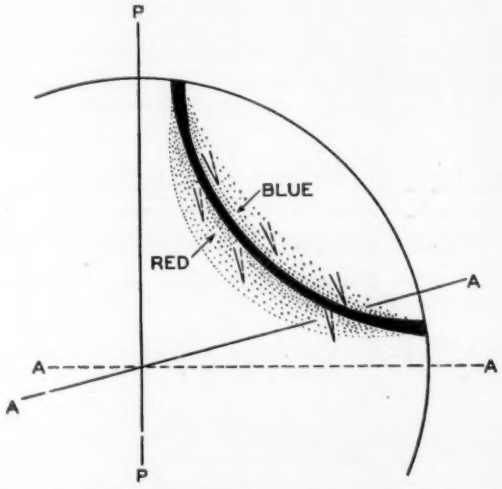

FIG. 5. Relation of colored fringes in the polarization figure of an isotropic mineral to vibration directions of red and blue light. Vibration directions for red light shown by dashed lines, vibration directions for blue light shown by solid lines. PP′, plane of polarizer. Plane of analyzer has been rotated from AA to A′A′. White light.

If the phase shift is small, the ellipse is narrow, the ray approaches the plane-polarized condition, and virtual extinction results. This is the case for most ore minerals. As the phase shift increases toward 90°, however, the ellipse becomes broad, and the contrast between the positions of maximum and minimum illumination decreases. The degree of ellipticity for a given reflected ray is a function of the indices of refraction and absorption of the mineral, but for a given wavelength of light it is also a function of the angle of incidence. In the optical system of the reflecting microscope, under conoscopic observation, ellipticity of the ray reflected from a given point should increase in general with

the distance of the point from the optical center of the field and from the two diameters of the field that are respectively parallel and perpendicular to the plane of the polarizer. If a mineral producing strong ellipticity is under observation and the analyzer is now rotated, the isogyres will move out into one pair of quadrants or the other, depending on the direction of rotation. In the portions of the isogyres in the vicinity of the diagonal of the field that bisects the isogyres, however, ellipticity of the reflected rays may be so strong that only partial extinction is produced. The area of partial extinction will spread from the diagonal as the isogyres move outward. If the ellipticity is the same for all wavelengths of light, the midportions of the isogyres will become gray. If the ellipticity varies markedly for different wavelengths, the isogyres will be colored, as in the case of gold. Copper shows a strong orange-red coloration of the isogyres. This property is here designated as *dispersion of the ellipticity*, symbol DE.

The usefulness of two dispersion properties discussed and defined in the preceding section is not yet fully apparent to us because our studies have thus far been focussed on the anistotropic minerals, and recognition of the dispersion

TABLE 1

OBSERVATIONS OF POLARIZATION FIGURES—ISOTROPIC MINERALS.

Mineral	Description of figure with analyzer rotated from crossed position	Relative dispersion of the reflection rotation	Ellipticity	Dispersion of ellipticity
Gold	End portions of isogyres black; mid-portions of isogyres and center of field yellow-orange.	Masked due to ellipticity	Strong	Strong
Silver	End portions of isogyres black; mid-portions of isogyres and center of field yellow-white	Masked due to ellipticity	Strong	Probably low
Copper	End portions of isogyres black; mid-portions of isogyres and center of field coppery pink	Masked due to ellipticity	Strong	Strong
Galena	Black isogyres with distinct reddish fringes on concave sides; white field	Red > blue, low	Nil	Nil
Sphalerite	Black isogyres with red fringes on concave sides; blue fringes indistinct	Red > blue, low	Nil	Nil
Magnetite	Black isogyres with faint red fringes on concave sides	Red > blue, weak	Nil	Nil
Tetrahedrite	Black isogyres with faint red fringes on concave sides; white field	Red > blue, weak	Nil	Nil
Pentlandite	Black isogyres on white field	Nil	Nil	Nil
Pyrite	Black isogyres with distinct red and blue fringes	Blue > red, moderate	Nil	Nil
Bravoite	Black isogyres with distinct red and blue fringes	Red > blue, moderate	Nil	Nil

TABLE 1—*Continued*

Mineral	Description of figure with analyzer rotated from crossed position	Relative dispersion of the reflection rotation	Ellipticity	Dispersion of ellipticity
Gersdorffite	Black isogyres; red fringes faint, blue fringes more distinct	Red > blue, low	Nil	Nil
Franklinite	Black isogyres with faint but distinct red and blue fringes	Red > blue, low	Nil	Nil
Chromite	As for franklinite			
Alabandite	Black isogyres with faint red fringes on concave sides	Red > blue, weak	Nil	Nil
Digenite	Black isogyres with strong red and blue fringes	Red > blue, strong	Nil	Nil
Violarite	Diffuse figure in all positions; material probably fine-granular	Red > blue, low	?	?
Cobaltite	Black isogyres with greenish yellow on concave sides; field between isogyres pinkish. Specimen is faintly anisotropic.	?Blue > red, distinct*	Nil	Nil
Bornite	Black isogyres; areas on concave sides yellow-green, field between isogyres pinkish gray	?Blue > red, distinct*	Nil	Nil
Argentite	Black isogyres with distinct red and blue fringes	Red > blue, moderate	Nil	Nil
Metacinnabar	Black isogyres with distinct blue on convex sides	Red > blue, low		

* The significance of this type of color pattern is not certain.

properties of isotropic minerals has come only as a byproduct of study of the theoretical principles underlying the behavior of polarization figures of anisotropic minerals. The effects for some isotropic minerals are striking; thus gold, pyrite, and chalcopyrite (which is nearly isotropic) can be distinguished instantly from their polarization figures. We have reason to believe that further investigation will enlarge the range of known dispersion phenomena for isotropic minerals and their usefulness in mineral identification.

Observations thus far made on a limited group of isotropic minerals are recorded in Table 1.

Anisotropic Transparent Minerals.—The optical relationships that cause the polarization figures of anisotropic minerals are complex. A transparent uniaxial mineral cut perpendicular to the *c*-axis gives the same figure as a transparent isotropic mineral, and the figure shows the same basic behavior as does the figure of an isotropic mineral on rotation of the analyzer or on rotation of the stage. A section oblique or parallel to the *c*-axis, however, behaves quite differently. This behavior is a consequence of the anisotropism.

If monochromatic light is used, plane-polarized light perpendicularly incident on a polished surface of a uniaxial mineral is in general broken into two

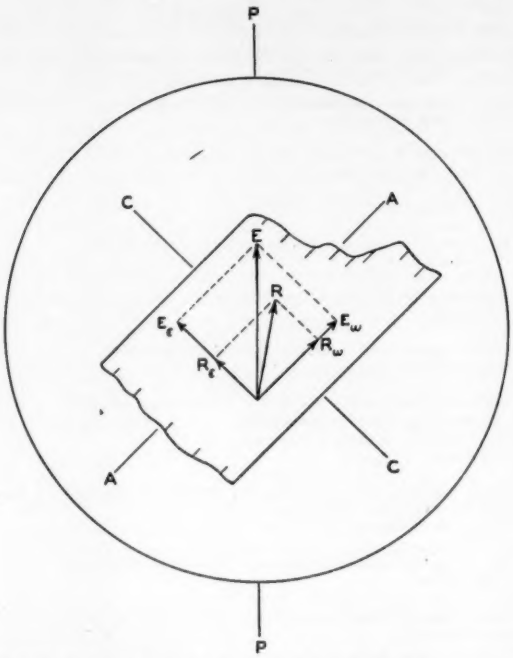

FIG. 6. Rotation of a plane-polarized ray by reflection from a polished section of a uniaxial mineral cut obliquely to the *c* axis. PP′, plane of polarizer; CC, trace of *c* axis; AA, trace of plane of horizontal crystallographic axes. E, azimuth of vibration of incident ray; E_ω, component of incident vibration parallel to AA (vibration direction of ordinary ray); E_ϵ, component of incident vibration parallel to CC (vibration direction of extraordinary ray). R, azimuth of vibration of reflected ray; R_ω, component of reflected vibration parallel to AA; R_ϵ, component of reflected vibration parallel to CC. Monochromatic light.

rays, one vibrating parallel to the trace of the *c*-axis, the other parallel to the trace of the plane of the horizontal axes of the crystal.[6] If the stage is rotated until either the trace of the *c*-axis or the trace of the plane of the horizontal axes is parallel to the trace of the vibration plane of the polarizer, light from the polarizer incident upon the surface is reflected back as plane-polarized light with its azimuth of vibration unchanged. If the analyzer is inserted and is *exactly crossed* with the polarizer, extinction results and the section becomes dark. Extinction therefore occurs four times in a 360-degree rotation of the stage. *Provided the nicols are exactly crossed and the objective is free of strain,* the positions of extinction are 90 degrees apart.

[6] Berek, Max, Optische Messmethoden im polarisierten Auflicht: Fortschr. der Miner., Krist., und Petrog., vol. 22, pp. 1–104, 1937.

In all intermediate positions of the stage, rotation of the azimuth of vibration of the incident light is produced by the mineral, and this rotation is at a maximum when the section lies 45 degrees in either direction from an extinction position. The rotation is due to the fact that at all positions of the stage, other than the extinction positions, light incident on the surface is broken into

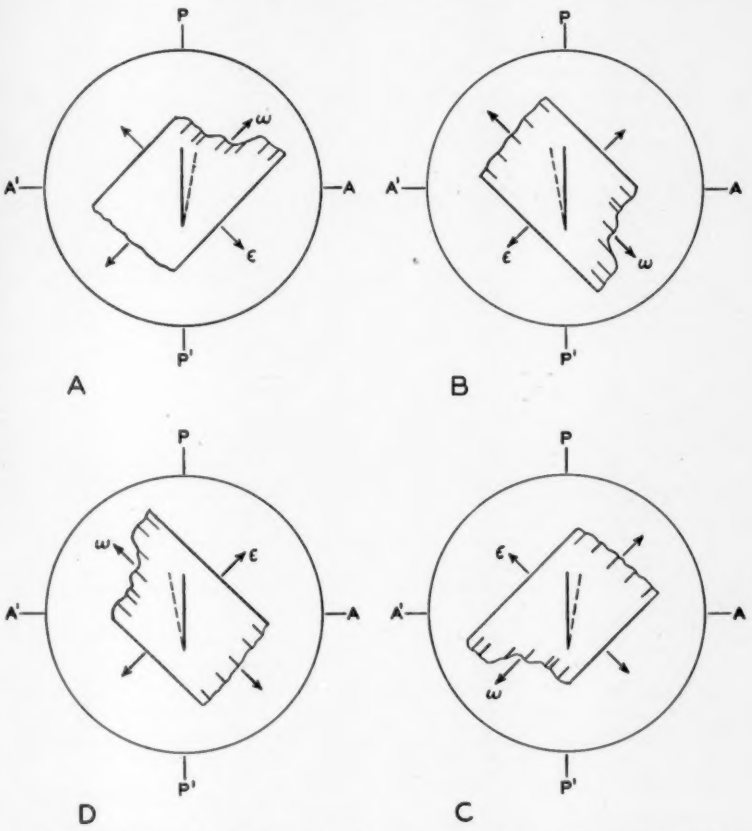

FIG. 7. Rotation of the plane of vibration of an incident plane-polarized ray by reflection from a polished surface of a uniaxial mineral cut obliquely to the *c* axis. Rotation is shown for each of the four diagonal positions of the mineral. PP′, plane of polarizer; A′A, plane of analyzer; ω, vibration direction of the ordinary ray in the mineral; ε, vibration direction of the extraordinary ray in the mineral. Lines extending in from the edges of the mineral grain represent traces of the basal cleavage of the mineral. Solid line in center of mineral grain shows vibration direction of incident ray; dashed line shows vibration direction of reflected ray. Monochromatic light.

two components that in general are reflected back with different amplitudes (Fig. 6). The reflected ray is the vectorial sum of these two components and, as shown in the figure, has a plane of vibration that is rotated with respect to the vibration plane of the incident light. As shown in Figure 7, the rotation is alternately clockwise and counterclockwise in the four quadrants defined by the traces of the two vibration directions in the mineral section. It will be noted that with respect to a given crystallographic element in a mineral (cleavage, elongate crystal habit, or the like), two cases are possible. In Figure 7, the rotation of the plane of vibration is toward the crystallographic element, in this case a cleavage. The sense of this rotation with respect to a given crystallographic element is, for a given mineral, a fundamental optical property. The case shown in Figure 7 is defined as positive rotation sense. The opposite case is defined as negative rotation sense. It is proposed that in descriptions of minerals the notation used be as in the following examples:

Mineral X — RS (+) cl. (001) = rotation sense positive with respect to trace of basal cleavage.

Mineral Y — RS (—) *c*-axis = rotation sense negative with respect to the trace of the *c*-axis.

Mineral Z — RS (+) tw. (100) = rotation sense positive with respect to trace of twinning on (100).

The procedure for determining this property is described in a succeeding section.

If now a high-power objective is used, a pinhole ocular is substituted for the ordinary ocular, the nicols are exactly crossed, and the mineral section is turned until one of its vibration directions is parallel to the polarizer, a "uniaxial" cross is again seen. The arms of the cross appear because along the north-south and east-west meridians incident light is vibrating either parallel or perpendicular to the planes of incidence, and parallel to the trace of one of the vibration directions of the mineral. The vibration planes of the reflected rays are therefore not rotated, and the rays are extinguished in the analyzer. In the four quadrants of the field lying between the arms of the cross, the vibration planes of the incident rays undergo rotations that are partly simple reflection rotations as with isotropic minerals, partly rotations due to the anisotropy of the mineral. The resultant vibration directions are divergent from the plane of the polarizer. Part of each ray therefore passes through the analyzer, and the quadrants are illuminated.

Behavior of the Figure as the Analyzer is Rotated.—If monochromatic light is used, the behavior of the figure as the analyzer is rotated is the same as that of the figure of an isotropic mineral. The figure breaks into two isogyres that move progressively outward into opposite quadrants as the rotation of the analyzer is increased. If white light is used, colored fringes may appear on the isogyres. These are due, as with isotropic minerals, essentially to *dispersion of the reflection rotation,* and are interpreted in the same manner. Red fringes on the concave sides of the isogyres indicate $DR_r = r > v$; blue fringes on the concave sides of the isogyres indicate $DR_r = v > r$.

Behavior of the Polarization Figure as the Stage is Rotated.—When

monochromatic light is used, then as the section is rotated from an extinction position, the cross separates into two "isogyres" similar to those of an acute bisectrix interference figure produced by a transparent biaxial mineral in convergent light (Fig. 8). The isogyres move out progressively as the stage is rotated. Maximum separation is reached when the stage is rotated 45 degrees from an extinction position. Depending on the direction of rotation of the stage and the particular extinction position, the isogyres will move into either the NW and SE quadrants or the NE and SW quadrants. With a 360-degree rotation of the stage, movement of the isogyres alternately into the NW-SE quadrants and the NE-SW quadrants takes place twice.

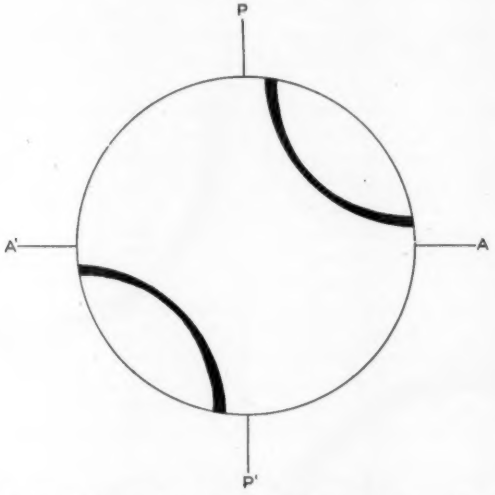

FIG. 8. Polarization figure of an anisotropic mineral at one of the 45-degree positions. PP', plane of polarizer; A'A, plane of analyzer.

The relationships responsible for this behavior are shown graphically in Figure 9. In the discussion of the polarization figure conoscopically obtained from an isotropic mineral it was shown that rotations of the planes of vibration of the incident rays are produced by reflection. Let us now consider the case of a uniaxial mineral that has been rotated on the stage to one of the 45° positions. In this case, the directions of simple reflection rotation for the various quadrants are as indicated by the diagrams on the margins of Figure 9. Light incident on the surface along the north-south diameter of the field is not rotated by simple reflection but is rotated clockwise owing to the anisotropy of the mineral. Part of it therefore passes through the analyzer, so that the north-south diameter is no longer a locus of extinction. The same condition holds along the equator of the field. The effective rotation within the quadrants defined by the isogyres, however, is essentially the resultant of two rotations, one resulting

from anisotropy of the mineral, the other from convergence and simple reflection. These two rotations are opposite in sense in the northeast and southwest quadrants; hence along the diagonal of the field passing through these quadrants, there will be some one point in each of the two quadrants at which the rotation due to reflection is exactly compensated by the rotation due to the mineral. This is shown in the small diagrams opposite these quadrants. These points will be the apices of the isogyres at the 45-degree position of the stage. Consider now a point on the circle X, lying on a diagonal OS between the N-S meridian and the diagonal OQ. At this point, the rotation due to reflection is less than at point B, because prior to reflection the divergence of the azimuth of vibration of the incident ray from the plane of incidence was less than at point

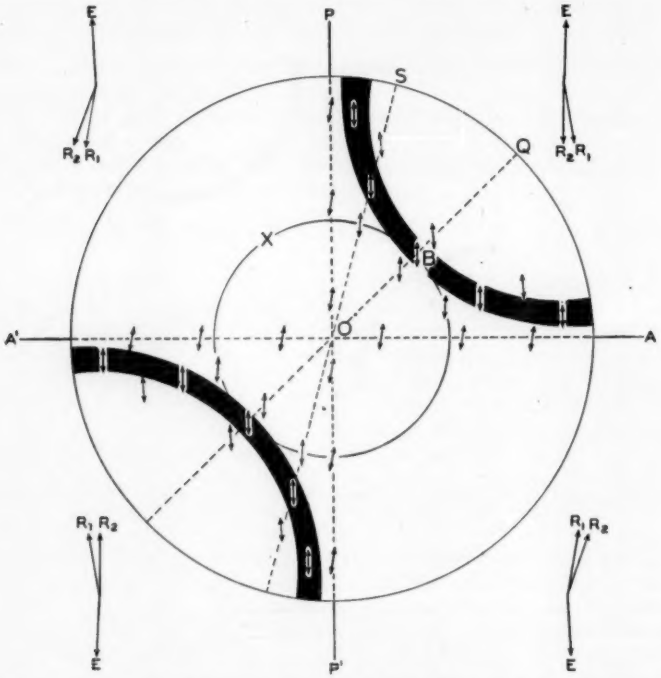

FIG. 9. Formation of isogyres of the polarization figure of an anisotropic mineral at one of the 45-degree positions. PP', plane of polarizer; A'A, plane of analyzer. In main diagram, double-headed arrows show vibration directions of rays reflected from various points. The rotation produced by the mineral is clockwise. The small diagrams outside the main diagram show, for a point in each quadrant lying at the intersection of circle X with the diagonal passing through the quadrant, E = azimuth of vibration of an incident ray, R_1 = azimuth of the reflected ray after reflection rotation, R_2 = azimuth of vibration of the reflected ray after rotation by reflection plus rotation due to the anisotropy of the mineral. Monochromatic light.

B. On line OS the point at which the rotation due to reflection is equal to the rotation due to anisotropy of the mineral will therefore be outside circle X. Similarly, points of compensation on other radii lying still nearer the N-S diameter will lie successively farther out. The summation of such points for the entire quadrant gives the isogyre. Precisely the same relations will hold for the southwest quadrant. In the other two quadrants, the rotations due to reflection and to anisotropy of the mineral are in the same sense; hence compensation cannot occur. These two quadrants are therefore wholly illuminated. If the stage is now turned in either direction through an extinction position to the next 45-degree position, the mineral produces a counterclockwise rotation. Compensation will therefore occur in the northwest and southeast quadrants, where the isogyres will appear.

If this explanation is correct, then for any given microscope system the maximum separation of the isogyres is a function of two things: (1) the rate at which the reflection rotation increases outward from the center of the field and away from the north-south and east-west diameters of the field, and (2) the amount of rotation due to anisotropy of the mineral. The rate of increase of the reflection rotation is essentially a function of the convergence produced by the objective, but it is also a function of the indices of refraction of the mineral. It must therefore vary somewhat with the crystallographic orientation of the section of the mineral under observation. The rotation due to anisotropy of the mineral is a function of the birefringence; for a given uniaxial mineral it reaches a maximum in sections parallel to the *c*-axis. Studies of sections of various orientations indicate that the maximum separation of the isogyres is likewise given by sections cut parallel to the *c*-axis. Furthermore, the maximum separation increases with the rotation due to anisotropy of the mineral and is therefore essentially a function of the rotation. This function is a specific property of the mineral for a given microscope system. The procedure for measurement of maximum separation is discussed in a subsequent section.

The validity of the above may readily be checked by inserting the normal ocular, using the usual extinction method to determine the values of the rotations produced by various uniaxial minerals, and comparing the results with the separations of the isogyres in polarization figures for these same minerals. To measure the angle for a given mineral, rotate the mineral 45 degrees from a position of extinction. The rotation of the analyzer then required to restore extinction is a measure of the rotation of the plane of vibration produced by the mineral. A relationship between these angles and the amount of separation of the isogyres shown in polarization figures of the minerals is immediately apparent. Observation of sections of varying orientations will also show that the separation reaches a maximum for sections parallel to the *c*-axis of a uniaxial mineral.

The angle of rotation as measured in terms of the maximum separation of the isogyres can be used as a basis for distinguishing minerals, but the actual rotation of the plane of vibration due to anisotropy of the mineral can be measured directly and entirely apart from the reflection rotation. Rays striking the optical center of the field are perpendicularly incident and therefore suffer no

reflection rotation. If the mineral now lies at one of the 45-degree positions, the number of degrees through which the analyzer must be rotated in order to restore extinction at the middle of the field is a direct measure of the rotation due solely to the anisotropy of the mineral. In practice, the analyzer is rotated in that direction which causes the isogyres to move together so that finally the dark cross is restored. The reading is taken for the precise point at which a perfect cross is formed. This angle is the *angle of rotation due to the anisotropy of the mineral,* or, more briefly, the *angle of rotation.* The form of the cross is so sensitive to a slight rotation of the analyzer that the compensation position can be determined far more accurately than by the normal method, which depends on the ability of the observer to detect the precise position of maximum darkness of the mineral grain.

Polarization Figures of Biaxial Transparent Minerals.—The polarization figures given by biaxial transparent minerals in reflected light are basically similar to those given by uniaxial minerals. The principal differences in the relations involved are those inherent in the lower symmetry of these minerals. For any wavelength of light, the maximum values of the angle of rotation will be given by a section parallel to the optic axial plane, the minimum by sections perpendicular to an optic axis. Figures given by sections perpendicular to an optic axis, however, will not have the same behavior as basal sections of a uniaxial mineral. The differences have little bearing on the behavior of polarization figures given by orthorhombic, monoclinic, and triclinic absorbing minerals and will not be discussed in the present paper.

Polarization Figures of Uniaxial Absorbing Minerals.—The polarization figures given by uniaxial absorbing minerals are basically similar to those given by uniaxial transparent minerals and can be analyzed microscopically in the same general manner. The two groups of figures are not identical, however, owing to the effects of absorption. Let an absorbing uniaxial mineral be placed under conoscopic observation and oriented on the stage so that its vibration directions are parallel respectively to the vibration directions of the analyzer and polarizer, which must be exactly crossed. Then all rays incident along the two diameters of the field that are parallel to the vibration planes of the nicols will be reflected back as plane-polarized rays with azimuths of vibration unchanged and will be extinguished in the analyzer. All other rays will have vibration planes inclined to their planes of incidence and, because the mineral is absorbing, each ray is resolved by the mineral into two rays that are vibrating at right angles to one another, have unequal amplitude, and have a phase difference with respect to one another. These two rays therefore give rise, in general, to a reflected ray that is elliptically polarized. In the analyzer each reflected ray is resolved into a linear vibration, the intensity of which is a function of the degree of ellipticity and the azimuths of the major and minor axes of the vibration ellipse. In general the effect of the phase shift is a rotation of the vibration plane of the incident light from the azimuth it would have if no phase difference were introduced. The apparent angle of rotation of the plane of polarization will therefore differ from the true angle of rotation. The ellipticity increases with increasing absorption of the mineral. For most anisotropic "opaque" minerals, absorption is low; hence ellipticity is small and the effect on the apparent

rotation of the angle of vibration is negligible.[7] It should be highest in general for minerals of high conductivity and reflectivity.

The effects of high absorption and ellipticity on the isogyres into which the figures separate upon rotation at other positions of the stage or of the nicol should be similar to those described for isotropic absorbing minerals. The writers have as yet found no uniaxial mineral for which the usability of the figures for determinative purposes is significantly affected by elliptical polarization. The rotation of the plane of vibration due to anisotropy, the relative dispersion of the reflection rotation, and the sense of rotation due to anisotropy are determinable for all uniaxial minerals thus far examined. It will be clear from the above, however, that the angles of rotation due to anisotropy are not the true angles of rotation but are functions of these angles more or less modified by the effects of absorption. For this reason, an angle measured for an absorbing mineral is here defined as the *apparent angle of rotation due to anisotropy of the mineral,* or, more briefly, the *apparent angle of rotation.* The symbol suggested for this property is A_r.

Polarization Figures of Orthorhombic, Monoclinic, and *Triclinic Absorbing Minerals.*—Optical relationships for orthorhombic, monoclinic, and triclinic minerals have been shown by Berek [8] and others to be far more complex than for transparent minerals of these same systems. Berek refers to them as minerals or crystals of lower symmetry, a convenient designation that will be employed in the present paper. In absorbing crystals of lower symmetry, there are no true optic axes. The two optic axes of transparent biaxial crystals are replaced by 4 directions or axes of circular polarization, the "Windungsachsen" of W. Voight.[9] So far as the writers have been able to determine, however, the polarization figures given by these minerals are, and should be, similar in their characteristics to those given by uniaxial absorbing minerals. Theory requires that perpendicularly incident plane-polarized light be elliptically polarized by reflection from sections of minerals of lower symmetry, save for sections perpendicular to one of the three optical symmetry planes of an orthorhombic crystal, or to the single optical symmetry plane of a monoclinic crystal. It might therefore be expected that the isogyres of polarization figures given by crystals of lower symmetry would in general be less distinct than those given by uniaxial crystals. In practice, the coefficients of absorption for most minerals of lower symmetry are apparently so small, and elliptical polarization so slight, that no consistent difference can be detected. In orthorhombic crystals, for any given wavelength of light, the four "Windungsachsen" are symmetrically disposed with respect to that one of the crystallographic symmetry planes which would be the optic axial plane of the crystal if it were fully transparent. Sections parallel to this principal plane, which will commonly be the plane of the *a* and *c* crystallographic axes, will give the maximum value of the apparent angle of rotation for the wavelength employed. From what is known of the dispersion characteristics of transparent orthorhombic crystals, however, special

[7] Schneiderhöhn, H., and Ramdohr, P., Lehrbuch der Erzmikroskopie, erster Bd., erste Hälfte, pp. 147–148, Gebrüder Borntraeger, Berlin, 1934.

[8] Berek, M., op. cit., 1937.

[9] Schneiderhöhn, H., and Ramdohr, P., op. cit., p. 134.

cases of dispersion in absorbing crystals of lower symmetry are probably to be expected. Dispersion phenomena are discussed in a subsequent section.

In monoclinic minerals, the crystallographic symmetry plane (010) is likewise the symmetry plane of the complex optical indicatrix. Sections parallel to the symmetry plane should give the maximum value of the apparent angle of rotation.

For triclinic absorbing crystals, little information as to the relations of optical properties to crystallographic directions appears to be available. Fortunately, triclinic absorbing minerals are not only very few in number but are very rare.

Dispersion Phenomena of Anisotropic Absorbing Minerals in White Light. —In white light polarization figures of many anisotropic absorbing minerals show color effects at the four positions of the microscope stage lying 45 degrees from the extinction positions. The color effects for some minerals are striking and are potentially very useful for mineral identification. The basic effects are color fringes on the isogyres, and the following discussion is confined to these, but colorations of the field away from the isogyres are shown by the figures of some minerals.

The color effects are functions of two kinds of dispersion: (1) *dispersion of the reflection rotation,* already described for isotropic minerals, and (2) *dispersion of the angle of rotation due to anisotropy of the mineral.* In polarization figures of anisotropic minerals these two properties cannot be isolated completely, but they can be analyzed qualitatively in such a way that they serve as a practical basis for mineral identification. The following explanation is qualitative and partly empirical.

Several cases arise, depending on whether the two types of dispersion offset or reinforce each other. The first and simplest case may be illustrated by the polarization figure of covellite. Let a section of this mineral cut obliquely to the *c*-axis or parallel to it be placed upon the stage and the mineral rotated to an extinction position, so that a cruciform figure is produced. Then let the analyzer be rotated so that isogyres move out into the northeast and southwest quadrants. The concave side of each isogyre and the adjacent part of the field is now strongly colored red, the convex side and the adjacent part of the field is colored blue. Let the analyzer be returned to the crossed position and the stage rotated 45 degrees in the direction that causes the isogyres to move out into the NW and SE quadrants. Strong color fringes again appear on the isogyres, but now the fringes are red on the convex sides of the isogyres, blue on the concave sides.

The relationships believed to be involved are shown in Figure 10A. The figure has two parts; part (1) shows the optical relationships along the isogyres produced from the cruciform figure by rotation of the analyzer. Along the red fringe blue light is cut out; hence vibration directions for blue must lie perpendicular to the plane of the analyzer (A′A). Similarly, along the blue fringe, red light is cut out, hence must be vibrating perpendicular to the plane of the analyzer. In part (2) of the diagram, the analyzer has been returned to the crossed position and the stage rotated 45 degrees. The rotation produced by

the mineral in this position is clockwise. The lines indicate, for a point on the red fringe and a point on the blue fringe, the vibration directions of red and blue rays. For the point on the red fringe, RO is the vibration direction for red light after the reflection rotation shown in part (1) of the figure. If the rotation due to anisotropy of the mineral were equal to the reflection rotation, the vibration direction for red light would be north-south and red light would be extinguished at this point. As red light is seen, the azimuth of the vibration must be to the right of north-south, at some position OR_1. Blue light, however, is extinguished at this point. This can only mean that the rotation for this wavelength produced by reflection is compensated by the rotation due to anisotropy of the mineral, so that the vibration direction is rotated from BO to OB_1. Relationships along the blue fringe are similarly represented. It follows from the diagram that the dispersion of the apparent angle of rotation is greater for red than for blue.

The *amount of dispersion of the apparent angle of rotation* (symbol DA_r) and the *relative dispersion of the apparent angle of rotation* are specific properties of the mineral. The procedure for measurement of the amount of dispersion is discussed in a subsequent section. The maximum value of the amount of the dispersion is given by a section of a uniaxial mineral cut parallel to the *c*-axis. For covellite both DR_r and DA_r are $r > v$. If the dispositions of the color fringes are exactly reversed, the dispersions are both $v > r$.

The second case is one for which we have as yet no ideal example (Fig. 10B) although a near approach is given by the figure of hausmannite. In part 1 of the figure, $DR_r = r > v$, and the vibration directions for red and blue light are as shown. Let us suppose, however, that the rotation due to anisotropy of the mineral for red light is equal to the azimuthal divergence of the vibrations for red and blue produced by reflection rotation plus the rotation for blue light due to anisotropy of the mineral. In this case, the vibration directions are as shown in part 2 of the figure for a point O on the isogyre, the notation being the same as in Figure 10A. We have the relation

$$\measuredangle ROR_1B_1 = \measuredangle ROB + \measuredangle BOR_1B_1.$$

At this point, both rays have vibration directions perpendicular to the plane of the analyzer and are extinguished. Darkness results; the isogyre is without color fringes. It will be seen from the diagram, however, that in this case both DR_r and DA_r are again $= r > v$. If in part 1 DR_r is $v > r$, then in part 2 DA_r must also be $v > r$.

The third possible case is shown in Figure 10C. In part 1 of the figure, DR_r is shown as $r > v$; the concave side of the isogyre has a red fringe, the convex side has a blue fringe. When the analyzer is returned to the crossed position and the mineral rotated to the 45-degree position, however, the disposition of color fringes is the same as that obtained in part 1. Using the same notation as before, we may express the vibration directions as in the figure. Study of the figure shows that this disposition of color fringes can only result if the relation

$$\measuredangle BOB_1 > \measuredangle ROR_1 - \measuredangle BOR$$

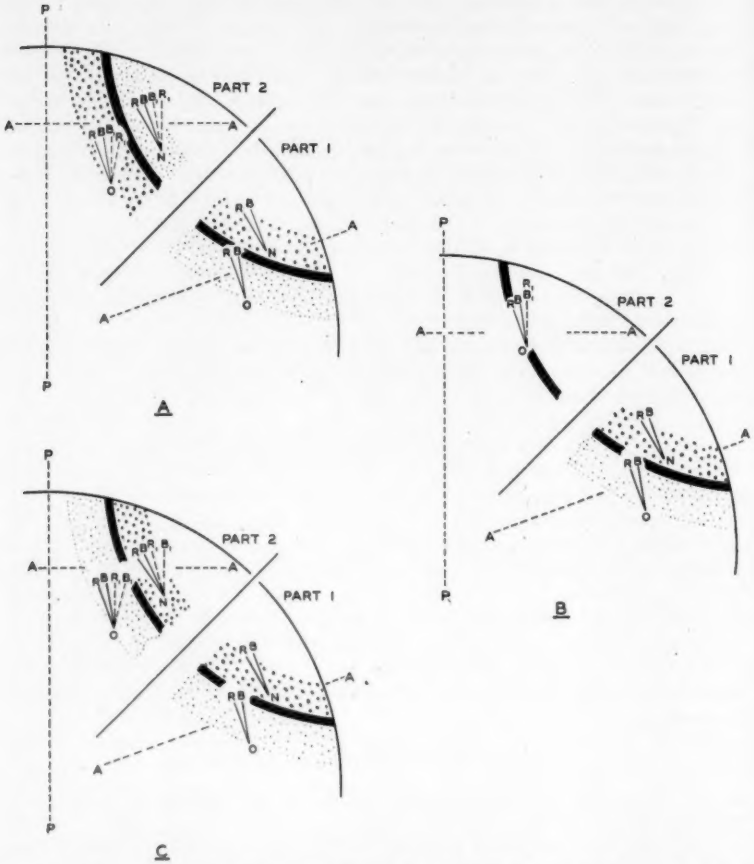

FIG. 10. Diagrams showing rotations of the azimuths of vibration of red and blue rays and their relation to color fringes exhibited by polarization figures of anisotropic minerals. In part 1 of each diagram, the mineral is at an extinction position; the analyzer (vibration plane A-A) is rotated counterclockwise. In part 2 of each diagram, the analyzer (vibration plane A-A) is crossed with the polarizer (vibration plane P-P), and the mineral has been rotated to one of the 45-degree positions at which it produces a clockwise rotation. OR and NR, azimuths of vibration of two red rays, incident at points O and N respectively, after reflection rotation. OB and NB, azimuths of vibration of two blue rays, incident at points O and N respectively, after reflection rotation. OB_1 and NB_1 are azimuths of blue rays, OR_1 and NR_1 are azimuths of red rays, after further rotation due to anisotropy of the mineral. Blue fringes are shown by stippling, red fringes by coarse dots.

holds. In this case, however, we do not necessarily have an indication of the relative dispersion of the apparent angle of rotation, for the angle for blue may be less than, equal to, or greater than the angle for red. The relative dispersion may be judged from inspection only if there is a marked contrast between the strength of the color fringes in part 1 and their strength in part 2. If the color fringes obtained in part 2 of the analysis are weaker than those obtained in part 1, then $DA_r = r > v$. This appears to be the case for the crystal face $(22\bar{4}3)$ of hematite, and for the pinacoid face (100) of columbite-tantalite. If the color fringes in part 2 are equal in intensity to those obtained in part 1, then $DA_r = 0$. We have as yet found no clearcut example of this relation. If the fringes are stronger in part 2, then $DA_r = v > r$. Niccolite is an example.

In Figure 10C, reversal of the fringes throughout would indicate $DR_r = v > r$, and $DA_r = v \gtrless r$.

If the relative dispersion of the apparent angle of rotation cannot be determined from the polarization figure by inspection, then it must be determined by measurement of the apparent angles of rotation for various wavelengths of light, according to the procedure described in a subsequent section. For uniaxial minerals, the maximum and characteristic value of the amount of dispersion will be given by a section or crystal face parallel to the *c*-axis. The characteristic values for orthorhombic and monoclinic minerals will be given by sections or faces parallel to that principal optic plane that bisects the acute angles between each pair of Windungsachsen. This plane corresponds to the optic plane in transparent biaxial minerals. It will more commonly be the plane of the *a* and *c* crystallographic axes in orthorhombic minerals and monoclinic minerals. Much work is probably necessary, however, before the dispersion characteristics of crystals of lower symmetry can be fully described and defined.

The distinction between dispersion of the reflection rotation and dispersion of the apparent angle of rotation is a useful one. The color patterns obtained in part 1 and part 2 of the above analysis often differ. Each is a specific property for a given mineral and will be of use in identification.

PROCEDURE OF OBSERVATION AND MEASUREMENT.

Apparatus Employed.—The results of conoscopic observations of ore minerals recorded below were made with a Spencer 43AC dual-purpose microscope. This microscope is a student-model petrographic microscope equipped with a vertical illuminating unit that takes the place of the objective used for petrographic examination of transparent minerals. Short-mount objectives corrected for observation without cover glass are supplied with the illuminating unit. The light source is a 6-volt, 2.75-ampere bulb that is inserted into a socket in the side tube of the illuminating unit and is controlled by a rheostat-transformer supplied with the unit. The bulb mount is centerable. The polarizer (and also the analyzer) is a polaroid disc. Aperture and field diaphragms are provided. The field diaphragm is very useful in ordinary observation under crossed nicols, because it can be used to eliminate all but the axial portion of the cone of rays coming from the light source. This gives an

illuminating pencil of essentially parallel rays, an essential condition for critical observation of anisotropism. During observation of polarization figures, however, the diaphragm must be kept fully open. The reflecting unit gives a choice between a half-aperture prism and a full-aperture glass plate. Only the glass plate can be used for obtaining polarization figures, but it is of the coated variety and gives brilliant illumination with the light source used. An analyzer that is rotatable through 90 degrees and has a graduated scale is an essential part of the equipment.

The objective used for conoscopic observation is one of the standard ones supplied by the manufacturer for use with the vertical illuminating unit. It is a short-mount, achromatic, coated objective, aperture 0.85 mm, magnification 40 ×. This model of microscope has no Bertrand lens. For conoscopic observation the microscope is first focussed on the mineral grain, the field diaphragm is opened wide, and the pinhole ocular then substituted for the ordinary ocular. Satisfactory figures have been obtained with this combination from carefully centered grains as small as .01 mm in minimum diameter. Grains .02 mm in diameter readily yield clear-cut figures. Figures have also been obtained from larger grains with a coated 20 ×, 0.52 mm short-mount objective, but they are too diffuse to be fully satisfactory.

An important feature of the apparatus described above is that the illuminating unit, which includes the polarizer, reflecting plate, and objective, can be rotated about the vertical axis (body-tube axis) of the microscope independently of the analyzer, which is housed in the usual position in the body tube. The illuminating unit can therefore be set in such a position that the crossed position of the analyzer falls in the middle of its graduated arc. The analyzer can then be rotated within the limits of its scale as much as 45 degrees in either direction from the crossed position. This makes it possible to measure both clockwise and counterclockwise rotations. Some microscopes are so built that the polarizer and reflecting plate cannot be rotated simultaneously about the tube axis of the microscope. The crossed position of the analyzer is usually at one end of the graduated arc of the analyzer; hence rotations can be measured only in one direction from the crossed position. To make both clockwise and counterclockwise readings possible, it will be necessary to reset the analyzer in its mount, so that the crossed position falls on the 45-degree mark of the scale.

The apparatus we have used gives excellent results, but there is no reason to believe that this particular type is essential for observation of polarization figures. A Bausch and Lomb research metallograph in our laboratory gives good figures. Four microscopes of other types available in our laboratory give poor results, but all are models of ancient vintage having uncoated plane-glass reflectors and optical systems that do not measure up to modern standards. Presumably they could be made usable by proper adjustment and by installation of modern coated, full-aperture reflectors. We are not sure as yet whether coated objectives are requisite, but undoubtedly they contribute to the brilliance and sharpness of the figures, because they have a higher light transmission than uncoated objectives.

Procedure.—Except as noted, it is assumed in the following discussion that

white light is being used for illumination. The first step in determining the rotation properties of a given mineral is precise crossing of the analyzer and polarizer. This can be done reasonably well by placing a fully isotropic strain-free mineral or polished plate on the stage of the microscope and observing it conoscopically. If the analyzer and polarizer are properly crossed, the "uniaxial" cross obtained will show no separation or distortion during a full rotation of the stage. The polaroids can be crossed with still greater precision by use of a moderately anisotropic section of a uniaxial mineral. When the polaroids are exactly crossed, such a section will show an undistorted cross at four positions precisely 90 degrees apart, in either monochromatic or white light. If an ordinary ocular is substituted for the pinhole ocular, the intensity of illumination will be equal at all four 45-degree positions, and in white light the color of illumination will be the same at all four of these positions. The objective must be strain-free and must be centered properly.

The polished section containing the mineral to be examined is then placed upon the stage and the microscope is focussed on the mineral grain. If the mineral appears isotropic, the polarization figure is then obtained by removing the pinhole ocular. If the cruciform figure shows no distortion as the stage is rotated, the mineral is either truly isotropic or the section under examination is a basal section of a uniaxial mineral. The latter possibility must be checked by examining a series of grains of the mineral. If the mineral is isotropic, the analyzer is rotated and the dispersion characteristics are determined by inspection.

If the mineral is anisotropic, the mineral is brought to one of the extinction positions under ordinary observation. Any crystallographic elements parallel or perpendicular to the extinction position are noted. The mineral is then turned 45° in either direction and the analyzer is again rotated until the mineral is at extinction. The direction of the rotation of the analyzer required to produce extinction is the direction of the rotation of the plane of vibration of the incident light produced by the mineral. The sense of rotation with respect to any known crystallographic elements parallel or perpendicular to the extinction position is thereby given.[10] The amount of this rotation can be read directly from the graduated arc of the analyzer. Extinction positions are difficult to determine precisely, however, particularly for minerals of appreciable dispersion. The angle of apparent rotation can be measured more readily and far more precisely from the polarization figure, as described below.

The analyzer is now returned to the crossed position, the ocular removed, and the pinhole ocular substituted. The stage is rotated until the figure forms an undistorted cross. The analyzer is then rotated, and if dispersion of the isogyres is shown, the relative dispersion of the reflection rotation, its strength, and the color pattern are noted. The analyzer is then returned to the crossed position and the mineral is rotated to one of the 45-degree positions. At this position the apparent angle of rotation due to anisotropy of the mineral is to

[10] The use of rotation sense in identification of ore minerals is subject to the same limitations as the use of optical elongation in identification of transparent minerals in transmitted light. It suffers from the additional handicap that crystallographic elements are commonly less easily identifiable in polished mineral sections.

be read. This can be done in either of two ways. If no Bertrand lens is available, the angle can be read in terms of the angular rotation of the analyzer necessary to restore the dark cross. If a Bertrand lens and micrometer scale are available, it should be possible to measure the angle in terms of the separation of the mid-points of the isogyres at the 45-degree position, expressing the angle in terms of units of the micrometer scale. The nature of equipment available will probably determine the method used for larger mineral grains. The use of the pinhole ocular probably will always be desirable for minute mineral grains. Whichever method is used, the stage should be rotated 90 degrees after the measurement has been made with the isogyres in one pair of opposite quadrants. The isogyres will then be in the opposite pair of quadrants. The measurement should then be repeated. The results for the two orientations of the isogyres should agree.

The position of the isogyres can also be used to indicate the direction of rotation of the plane of vibration produced by the mineral at the 45-degree position under observation. If the isogyres are in the NE and SW quadrants, the rotation produced by the mineral is clockwise. This can be confirmed by rotating the nicol clockwise; the cross seen at one of the 90-degree positions will be restored. Similarly it can be shown that if the isogyres are in the NW and SW quadrants at the 45-degree position of the mineral, the rotation of the plane of vibration produced by the mineral is counterclockwise.

If the isogyres show distinct fringes, the relative dispersion of the apparent angle of rotation must then be determined by comparison of the color fringes at this stage with those observed on rotation of the analyzer, and then by interpretation as outlined in the discussion of dispersion phenomena. The amount of the dispersion of the apparent angle of rotation, i.e., DA_r, can be determined roughly in white light if the red and blue fringes are well defined. With the mineral in the 45-degree position, rotate the analyzer until the blue fringes join at the center of the figure to form a cross. The rotation required, in degrees, measures the apparent angle of rotation for red. The measurement should be repeated with the stage rotated 90 degrees. The two values should agree within the limits of the error involved in reading the scale of the nicol. The same procedure is then repeated, this time with the red fringes. The rotation of the analyzer required to form a red cross at the center of the field is the apparent angle of rotation for blue. The difference between the two values is the dispersion of the apparent rotation. The value of the dispersion given by a section showing maximum anisotropy is a characteristic property of the mineral. For a uniaxial mineral this will be the section parallel to the *c*-axis; for a mineral of lower symmetry it will be given by a section parallel to the principal optic plane.

For accurate results it is necessary to determine the values of DA_r for many minerals by use of monochromatic light of appropriate wavelengths. This is particularly true for those minerals having values of A_r and DA_r that are small relative to the accuracy of measurement. The accuracy of measurements of these properties can be increased, however, in the following manner: With the nicols exactly crossed, rotate the mineral to one of the 45-degree positions. The isogyres are now at normal maximum separation. Rotate the analyzer,

clockwise or counterclockwise as may be necessary, until the uniaxial cross is exactly restored and record the scale reading on the analyzer. Now rotate the stage 90 degrees. At this position the isogyres will have approximately twice the normal amount of separation. Now rotate the analyzer in the opposite direction, until the cross is restored. The difference between the two scale readings on the analyzer, divided by two, is the apparent angle of rotation. If the whole procedure started with the isogyres at normal maximum separation in the NW and SE quadrants, it should be repeated starting with the isogyres at normal maximum separation in the NE and SW quadrants. The two values should agree. If they do not, the measurements were inaccurate, the analyzer and polarizer were not exactly crossed at the beginning, or the objective is not strain-free. The effect of this procedure is to increase the sensitivity of the measurement of the apparent rotation of the plane of vibration due to anisotropy.

Inasmuch as the rotation properties discussed above are functions of the orientation of any given anisotropic mineral, observations on a single grain will not give all the optical characteristics of a mineral. In most polished surfaces of ores, however, any given mineral is represented by a number of grains in random orientation, and one or more are likely to be oriented in or near the optimum position. In practice, the surface should be scanned between crossed nicols and polarization figures obtained from these grains that show strongest anisotropism. Measurements can then be made on the grain that shows maximum separation of the isogyres. Observations thus far made suggest that this "statistical" method will give results very close to the diagnostic values, for the rate of change of apparent angles of rotation in the vicinity of the orientation of maximum anisotropy appears to be small.

RESULTS OF OBSERVATION.

General Statement.—Work to date has been aimed primarily at checking the explanation of polarization figures and rotation properties given here and examining their potentialities as a means of identification of ore minerals under the microscope. Measurements of rotation properties have been made chiefly for the purpose of determining the range of these properties exhibited by ore minerals. Systematic determination and recording of data for all opaque mineral species will require protracted studies both of ordinary polished surfaces and of oriented sections of crystals of the various mineral species. The data presented below are given solely as an index of the validity of the theory offered and the potential value of polarization figures for mineral identification. The data are not reference data, for our equipment must be standardized and measuring devices improved before reference data can be established. As present microscope equipment was not designed with polarization figures in mind, modifications of existing equipment are needed. The modifications do not appear serious and should be kept to the minimum required for optimum sensitivity and accuracy of measurement. It is hoped that they can be introduced without increasing the cost of standard mineragraphic equipment appreciably.

Data Obtained.—Data obtained by conoscopic observation of various minerals are presented in Table 2. The measurements have been made on mineral grains in polished surfaces, except as noted. The minerals examined have been selected solely because they illustrate varying degrees of anisotropism, dispersion of the reflection rotation, and dispersion of the apparent angle of rotation due to anisotropy. The measurements are, again, not reference data; oriented sections have been used only for a few minerals. However, values of apparent angles of rotation in white light, apart from those obtained from oriented sections or crystal faces, were in every case made on grains selected because they appeared to show maximum anisotropism. The values given should therefore approximate the maximum and diagnostic values for the minerals.

The value given in the table for the apparent angle of rotation of the plane of vibration for a given mineral is that rotation of the analyzer, in degrees, required to restore the dark "uniaxial cross" after the mineral has been rotated to the 45-degree position. For some of the minerals, values of A_r are given only for white light. For others, values are given for red and blue light as well. We are not at present equipped to make accurate measurements in monochromatic light. The values were measured as a check on the interpretation of color fringes and recorded in the table for this same purpose. An arc-lamp was used as the illuminating unit. The values given in general are believed accurate within about 0.3 of a degree.

In general, the minerals in the table are listed in decreasing order of values of the apparent angles of rotation for white light. Arranged in this way, the data give a qualitative check on the validity of the methods discussed in previous sections. Those familiar with the appearance of ore minerals in polarized light will recognize that the minerals near the top of the table are those that show strong anisotropism; those at the bottom of the list are minerals of weak anisotropism. Similarly, inspection of the data given for dispersion of the apparent angle of rotation shows a correlation between strength of dispersion and brilliance and variety of polarization colors between crossed nicols.

In the column headed "Separation of isogyres," the spread of the isogyres when the mineral is rotated 45 degrees from an extinction position is given in terms of percentage of the field diameter. As would be expected, the separation decreases progressively with the value of A_r. The lowest separation shown by any anisotropic mineral thus far examined is that of the polarization figure of chalcopyrite; the figure is distorted as the stage is rotated, but even at the 45-degree positions the isogyres do not draw apart. At the other end of the range is covellite; the isogyres for red light lie outside the field at the 45-degree position, if the grain under observation is cut parallel to the *c*-axis or nearly so.

The values of maximum separation given in the table are rough estimates and only enough are given to indicate the range of separations and the possibilities for distinguishing minerals on this basis with suitable equipment. With a Bertrand lens and micrometer scale in the system, we hope that accurate measurements can be made in monochromatic light; the values thus obtained could be calibrated readily. The method should have the advantage of

TABLE 2.

OBSERVATIONS OF ANISOTROPIC MINERALS.

Mineral	Crystal system	Rotation sense	Relative dispersion of reflection rotation—DR_r	Apparent angle of rotation—A_r			Relative dispersion of apparent angle of rotation—DA_r	Amount of dispersion	Separation of isogyres in approx. percent of field diameter	Figure after rotation of analyzer	Figure at 45° position. Analyzer and polarizer crossed
				Blue	White	Red					
Covellite	Hex.	(−)cl. (0001)	r>v, low	19°	n.d.	35°±	r>v, very strong	11°±	red − 100 + blue − 90	Black isogyres; faint red fringe on concave sides, blue on convex sides	Brilliant red and blue figure on white field
Molybdenite	Hex.	(+)cl. (001)	?, very weak	13.3°	13.3°	13.0°	v>r, weak	0.3°	90	Black isogyres on white field	Black isogyres on white field
Stibnite (grain)	Orth.	(+)cl. (010)	r>v, moderate	6.3°	5.9°	5.1°	v>r, moderate	1.2°	70	Black isogyres; distinct red fringe on concave sides, blue on convex sides	Black isogyres with strong red fringes on concave sides and blue fringes on convex sides
Stibnite (cleavage)	Orth.		r>v, distinct	2.6°	2.5°	1.6°	v>r, moderate	1.0°		As for stibnite grain	Black isogyres with moderately strong red fringes on concave sides, blue fringes on convex sides
Berthierite	Orth.	(+)cl. (001)	Essentially nil	5.8°	5.1°	4.3°	v>r, moderately strong	1.5°		Black isogyres on white field	Black isogyres with pink fringes on concave sides, green on convex sides
Breithauptite	Hex.		r>v, distinct	5.0°	4.8°	4.2°	v>r, moderate	0.8°		Black isogyres; pale red fringes on concave sides, pale blue on convex sides	Black isogyres; pink fringes on concave sides; blue-green to yellow between
Miargyrite	Mono.		r>v, distinct	2.6°		4.0°	r>v, moderately strong	1.4°		Black isogyres. Distinct fringes, red on concave sides, blue on convex sides	Hazy isogyres; concave sides purple, field between isogyres orange-yellow
Hausmannite (1)	Tetrag.		r>v, distinct		3.5°		r>v, weak			Black isogyres. Distinct but pale fringes, red on concave sides, blue on convex sides	Black isogyres; concave sides pale blue. Field between isogyres pale pink
(2)	Tetrag.		r>v, low	2.5°		2.7°	r>v, weak	0.2°			
Niccolite	Hex.		r>v, weak	3.6°	3.4°	2.4°	v>r, moderately strong	1.5°		Black isogyres. Fringes pale, red on concave sides, blue on convex sides	Black isogyres; concave sides pink, convex sides green
Lollingite (1)	Orth.		Essentially nil		2.9°		v>r, moderately strong			Black isogyres, no definite fringes	Black isogyres; concave sides red, convex sides blue
(2)	Orth.		Essentially nil	2.2°		1.0°	v>r, moderate	1.2°			
Hematite, section //c-axis	Hex.		r>v, distinct		2.5°		r>v, distinct			Black isogyres. Fringes distinct, red on concave sides, blue on convex sides	Black isogyres; concave sides pale reddish, convex sides pale greenish

TABLE 2—*Continued*

Mineral	Crystal system	Rotation sense	Relative dispersion of reflection rotation—DR_r	Apparent angle of rotation—A_r			Relative dispersion of apparent angle of rotation—DA_r	Amount of dispersion	Separation of isogyres in approx. percent of field diameter	Figure after rotation of analyzer	Figure at 45° position. Analyzer and polarizer crossed
				Blue	White	Red					
Hematite *n*(2243) face	Hex.		r>v, distinct		1.6°		r>v, distinct			Black isogyres; fringes pale but distinct. Red, convex; blue, concave	Black isogyres; concave sides reddish, convex sides green
Pyrrhotite	Hex.	(−) parting (0001)	nil	2.1°	2.4°	2.7°	r>v, low	0.6°		Black isogyres, no fringes	Black isogyres; concave sides very pale blue, convex sides orange
Rutile (110) face	Tetrag.	(+) *c*-axis	r>v, low		2.1°		?, weak		50	Black isogyres. Fringes pale, red on concave sides, blue on convex sides	Black isogyres on white field; figure marred by internal reflections
Enargite (1)	Orth.		Essentially nil		2.1°		r>v, moderate			Black isogyres. No definite fringes	Black isogyres; concave sides blue, field between isogyres pink to red
(2)	Orth.		Essentially nil	0.8°		1.7°	r>v, moderate	0.9°			
Teallite	Orth.	(+)cl. (001)	Essentially nil		1.4°		Essentially nil		40	Black isogyres. No definite fringes	Black isogyres; concave sides purple, convex sides greenish gray
Arsenopyrite	Mono.		v>r, low	2.4°	1.3°	0.6°	v>r, moderately strong	1.8°		Black isogyres. Fringes weak, red on convex sides, blue on concave sides	Black isogyres; concave sides pink, convex sides green
Pyrargyrite	Hex.		r>v, moderate		1.2°		?r>v, weak			Black isogyres. Fringes moderately strong. Red on concave sides, blue on convex sides	Black isogyres; concave sides pale pink, convex sides pale blue
Columbite tantalite *a*(100) face	Orth.		r>v, low		1.2°		?, weak			Sharp black isogyres. Very pale fringes, red concave, blue convex	Black isogyres; pale fringes, blue on concave sides, red on convex sides
Marcasite	Orth.		v>r, low	2.7°	1.1°	0.3°	v>r, strong	2.4°	20	Black isogyres. Pale fringes, blue on concave sides, red on convex	Black isogyres; concave sides pink, center of field bright green
Bismuth	Hex.		Essentially nil		1.0°		?v>r, weak			Black isogyres on white field	Black isogyres on white field. Faint color fringes
Chalcopyrite	Tetrag.		v>r, low		0.5°		?, weak		<5	Black isogyres; distinct red fringes on convex sides, blue fringes on concave sides	Black cross, slightly distorted on rotation of stage.

greater rapidity than measurement by rotation of the analyzer. It may not be applicable, however, to small grains.

The measurements for stibnite and hematite are of particular interest. The optic plane for stibnite is known to be the plane of the *b* and *c* crystallographic axes.[11] The cleavage of stibnite (010) is normal to this plane. Sections parallel or nearly parallel to the *bc* plane should give greater apparent rotation of the plane of polarization and greater dispersion of the apparent rotation than cleavage surfaces. In the table, the grain measured was selected as showing maximum anisotropism; both A_r and the amount of dispersion of the apparent angle of rotation are higher for this grain than for the cleavage surface. Hematite offers another check on the validity of the data. Theory requires that maximum values for A_r be given by a section parallel to the *c*-axis; all sections and crystal faces oblique to the *c*-axis should give lower values of A_r. The results recorded in the table are consistent with theory.

The table is unavoidably deficient in that it does not show the range of color contrasts in the figures for various minerals. As previously explained, these color contrasts, for a given microscope system, are functions of dispersion; i.e., they are properties of each mineral. It is already evident that the color patterns for some minerals will have diagnostic value in themselves. Under "Remarks" an attempt is made to describe the color patterns for each mineral, but the authors are conscious that the descriptions do scant justice to the figures.

The table suggests that the values of the apparent angle of rotation for most anisotropic minerals range between a few tenths of a degree and 6 degrees. In terms of actual measurements this means a range between a few tenths of a degree and 12 degrees, because if this rotation is compensated successively at two 45-degree positions 90 degrees apart, as described in the section on procedure, the actual angle read is the difference between the two extreme positions of the analyzer. This is twice the angle of apparent rotation. The range of apparent angles of rotation is thereby effectively enlarged, and it is clear that they will be of use for determinative purposes. Thus miargyrite and pyrargyrite are readily distinguished by the difference in their angles of apparent rotation. Rutile and columbite-tantalite are likewise easily distinguishable on this basis.

Covellite and molybdenite are noteworthy for their extraordinarily high apparent angles of rotation, and thereby stand apart from all other minerals on the list. The value of A_r for red light is so high for covellite that the angle cannot be measured accurately, for as the analyzer is rotated toward the compensation position, the overall illumination of the field increases so much that the isogyres of the figure are obscured.

The data given in the table for amounts of dispersion are not all measured from grains of maximum anisotropism, hence are not fully indicative of the range of dispersion. Apart from the extraordinarily high dispersion of covellite, most of the values given range from 0 degrees to 1.8 degrees. This range

[11] Bailly, R., Utilisation des radiations infra-rouges dans les recherches minéralogiques et en particulier pour la détermination des minéraux opaques: Soc. Franc. Minér. Bull., vol. 70, p. 90, 1947.

is not great, but again the effective range in measurement is twice this value; i.e., 3.6 degrees. This is sufficiently large so that it will have diagnostic value, particularly because it is attended by a striking range of dispersion color patterns. Thus stibnite and molybdenite can be distinguished instantly on the basis of their dispersion characteristics alone; likewise miargyrite and pyrargyrite. It is hoped that other pairs of minerals that have consistently proved difficult to distinguish will show contrasts in apparent angles of rotation or dispersion, or both.

Relative dispersion of A_r for red and blue light also promises to be of value in mineral identification. Most of the minerals examined show $DA_r = v > r$. Those minerals that show the opposite relation therefore stand apart and should be readily distinguished on this basis. Joint consideration of DR_r and DA_r should permit further subdivision. Thus arsenopyrite and lollingite are readily distinguished by comparison of their dispersion phenomena given first with rotation of the analyzer and, second, with rotation of the stage with the analyzer in the crossed position.

In much determinative work measurement of the amount of dispersion should be unnecessary, because the color patterns of the figures in white light, together with qualitative determination of the dispersion formulas, will suffice for distinction of certain pairs of minerals. The data given in the table indicate that the rules for qualitative determination of dispersion formula given in a previous section are valid. Difficulty may arise, however, where dispersions are weak and color fringes indistinct or of colors other than blue or red. We have found that our interpretations of such fringes are not infallible and that measurements of DA_r in monochromatic light are then a necessary check. Brilliant illumination facilitates both qualitative determinations and actual measurements.

SOURCES OF INCONSISTENCY IN OBSERVATIONS OF POLARIZATION FIGURES WITH THE MICROSCOPE.

General Statement.—From the nature of the method used for conoscopic observation and measurement, and from theoretical considerations, it is evident that there are several possible sources of inconsistency in measurements of rotation properties with the microscope. The writers are aware of three possible sources, as follows:

(1) The effects of grinding and polishing on the optical characteristics of the mineral section.
(2) Errors in technique of measurement.
(3) Optical defects of the microscope system.

The influence on the consistency of measurements is not the same for all three sources; in the following sections an attempt is made to evaluate them.

Effects of Grinding and Polishing.—The effects of grinding and polishing on the optical properties of minerals in polarized light have been discussed in detail by Berek.[12] Grinding and polishing tend to develop a flowed amorphous

[12] Berek, M., op. cit., pp. 29–30, 99–103.

layer over the surface of a mineral. The thickness of this layer varies with the polishing and grinding methods used, with the time of polishing and grinding, and with the tenacity and hardness of the mineral. Other things being equal, the thickness of the layer will be greatest for soft, ductile or malleable minerals and least for hard, brittle minerals. From Berek's discussion it appears that under certain conditions the ellipticity of reflected vibrations for a given mineral may be significantly altered, but that for a given ray the azimuth of the major axis of the vibration ellipse, which determines the values of A_r and DA_r obtained by the conoscopic method, will not be significantly changed.

Errors in Technique of Measurement.—Errors of measurement inherent in the type of equipment we have used are mentioned in a preceding section. The limits of error due to these causes can be narrowed greatly by relatively slight modification of the equipment. Other sources of inconsistent values are failure to cross the nicols precisely before making measurements and the presence of surface films on the specimen under observation. If the nicols are not crossed, true values of the rotation properties will not be obtained. The errors are likely to be particularly serious for minerals of moderate to strong dispersion. For minerals of weak dispersion, failure to cross the nicols properly will result in anomalous dispersion effects that may lead to incorrect interpretation.

Tarnish and other surface films that are acquired by polished surfaces in the average laboratory atmosphere have marked effects on polarization figures. For this reason, surfaces should be buffed lightly and washed prior to examination.

Optical Defects in the Microscope System.—Experiments with apparatus available in our laboratory indicate that clear polarization figures are obtained only if the microscope system used fulfills rather rigid requirements. These are (1) a strong source of illumination, (2) a full-aperture reflecting device of a type that has a high reflectance and causes a minimum of rotation of the vibration planes of the rays coming to and from the polarizer, (3) an objective free of strain, and (4) a reflecting mineral surface that is perpendicular to the axis of the microscope. Experience suggests, unfortunately, that some types of ore microscopes currently in use will not fulfill these requirements, particularly the older models.

Inasmuch as detection of dispersion requires figures with clear bright color fringes, a brightly illuminated field is a prime requisite. The type of source required will probably vary with the reflecting power of the reflecting device furnished with a particular illuminator. Arc lamp illumination is probably requisite unless the plate is coated to increase its reflectance and its transmission of the rays reflected back through it from the mineral surface. Whatever source is used, the light supplied must be diffuse. The polarization figures obtained will be marred if an image of the filament or arc appears in the conoscopic field of view.

The reflecting device must be of the full aperture type. Prism illuminators give only half a polarization figure. The surface of the device must be precisely perpendicular or parallel to the plane of the polarizer, and its axis of rotation must be perpendicular to the axis of the microscope. In addition, the

reflecting device must be such that the vibration planes of rays in the beam coming from the polarizer undergo a minimum of rotation at the surface of the reflecting device. This subject has been discussed fully by Berek [13] and more briefly by Foster.[14] The general effect of an inferior reflecting device is to superpose upon the figures described in the present paper a diffuse illumination that decreases the sharpness of the figures and, if marked, obscures or destroys their color patterns.

Neuerburg [15] described the effects of rotation of objectives on figures obtained by conoscopic observation of isotropic minerals. Rotation of the objectives through 360° caused the figures to behave as do figures of anisotropic minerals when the microscope stage is rotated. The writers have produced similar effects by rotation of objectives and believe that they are due to strain in the objectives. We have available six 4-mm short-mount objectives of identical type. If these objectives are successively inserted into the same microscope system and rotated, the figure of an isotropic mineral will show a behavior similar to that described by Neuerburg. The degree of the effects varies with the objective and ranges from diffuseness of the figure or asymmetry of the pattern of color to complete separation of isogyres. For every objective there are four positions 90 degrees apart at which an undistorted, sharp cross of symmetrical color pattern is given when the vibration planes of polarizer and analyzer are precisely crossed.

Neuerburg considered but rejected the idea that strain is the cause of the phenomena described, for at least one of the objectives had been determined as strain-free by the normal test with the interference figure given by a plate of mica. We do not question that the objective was strain-free by normal standards, but suggest that the production of perfect polarization figures in reflected light provides a far more sensitive test for the presence of strain in objectives than the test with a mica plate.

With the better of the objectives available in this laboratory, the effects of strain are so slight that they cause no difficulty. With the others, we have found that by unscrewing the objective just enough to bring it to the proper azimuth, clear, undistorted, symmetrical figures can be obtained. If this is done, then the presence of strain in the objective causes no measurable error in the determination of rotation angles or difficulty in determining dispersion properties. When the objective is properly oriented and the nicols exactly crossed, dispersion colors shown as the mineral is rotated on the stage will always be the same at all four 45-degree positions.

It has been suggested above that errors may be introduced into the measurements if the polished surface is not perpendicular to the axis of the microscope. Deviation from the perpendicular is indicated if the center of the polarization figure does not lie at the center of the field of view. We have not been troubled by this condition and have therefore not determined the magnitude of errors that may arise in this way.

[13] Berek, M., op. cit., pp. 10–15.

[14] Foster, L. V., A study of polarized vertical illumination: Opt. Soc. America Jour., vol. 28, pp. 127–129, 1938.

[15] Neuerburg, G. J., op. cit., 1948.

APPRAISAL OF THE METHOD.

The microscopic study of ore minerals has long been handicapped by the paucity of the optical properties readily determinable for these minerals. Optical determinations have been far less important than in the identification of transparent minerals. Although much work remains to be done before the value of rotation properties in ore mineral identification can be fully appraised, it appears probable that they will contribute substantially toward solution of identification problems. The phenomena described are striking and are easily and quickly analyzed. Elaborate modifications of existing standard mineragraphic equipment appear unnecessary. Observations made thus far indicate that, in terms of the sensitivity of present-day equipment, the range of values of rotation constants for opaque minerals is wide and that the long-held belief that the angles of rotation are too small to be useful in mineral identification is no longer justified.

On the basis of rotation properties, it should be possible to subdivide both isotropic and anisotropic minerals into contrasting groups. The degree to which subdivision will be possible is not yet clear, but certain limitations can be envisioned. For some minerals, dispersion of the rotation angles is so small that distinct color fringes do not appear in white light with the equipment used. Modification of equipment may extend the range of sensitivity, but relative dispersion for blue and red light may not be determinable for some minerals. Likewise, it seems probable that future work will show that the rotation constants for many minerals differ only by small amounts. The fact that only sections of known orientation can be used for determining the absolute values of the rotation constants may be an additional limitation. In most polished surfaces, however, each mineral is represented by numerous grains in random orientation. The maximum values can therefore be found by measurements on a number of grains. Fortunately, preliminary observations suggest that the rate of change of the angle of rotation is small in the vicinity of the maximum point; hence measurements on a series of grains selected for strong anisotropism should yield a maximum result close to the true maximum value for the mineral.

Full theoretical treatment of the formation of polarization figures would require elaborate mathematical analysis of optical relationships that are far more complicated than those underlying the study of transparent minerals in transmitted light. The presentation in this paper is deliberately qualitative; it is an attempt on our part to apply certain of the fundamental findings of optical physicists to the practical problems of ore mineral identification. Full analysis we leave to those whose field is the treatment of mathematical optics; we hope, however, that this paper will lead to the practical application of a striking and often beautiful group of phenomena.

ACKNOWLEDGMENTS.

The investigation described in this paper stems from an initial observation by Green that an optical figure is produced by a Bausch and Lomb research metallograph when the ocular is removed. The observations recorded are the

work of both authors, but Cameron must assume responsibility for the theory of polarization figures and its applications as here presented.

We wish to acknowledge our heavy indebtedness to the work of Dr. Max Berek that has been cited in the text.[16] The explanation of polarization figures offered in this paper was largely made possible by his lucid exposition of the optics of opaque minerals in reflected light.

Our thanks are due to Prof. R. C. Emmons, of this department, and to Prof. R. Rollefson, Chairman of the Department of Physics, for helpful comments on the paper.

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April 25, 1950.

[16] Berek, M., op. cit., 1937.

EXPERIMENTS ON THE DEPOSITION OF IRON WITH SPECIAL REFERENCE TO THE CLINTON IRON ORE DEPOSITS.[1]

JOHN R. CASTAÑO AND ROBERT M. GARRELS.

ABSTRACT.

Laboratory experiments simulating conditions of formation of the Clinton iron ores show that significant quantities of ferrous iron can be carried in solution in aerated river waters of pH 7 or lower. If such waters enter a marine environment with solid calcium carbonate in equilibrium with the sea water, the iron is essentially completely precipitated as ferric oxide, both in the water and as direct replacement of the calcium carbonate. Quantitative data are presented relating both ferrous and ferric iron concentration to the pH and reduction-oxidation potential of the environment. Suggestions are made as to the major controls of iron deposition as oxide, silicate, or carbonate.

INTRODUCTION.

THE Clinton iron ores of New York have long been a subject of geologic research and discussion. Many different theories of origin have been suggested over a hundred year period of research, but recent papers, especially those by Alling (1)[2] and Gilette (5, 6), have discussed previous work critically, and have presented a picture of the geologic environment of formation that seems beyond serious dispute.

With the establishment of a clear-cut reconstruction of the stratigraphic, tectonic, and biologic environment, it now seems feasible to attack the chemical aspects of the problem within that framework. As Alling (1, p. 1011) states, "our knowledge of the chemistry is exceedingly scant . . . do not know what form the iron was, and, if different from what it is today how and what changes took place." Accordingly, the first section of this paper is a condensed recapitulation of the conditions of ore formation as culled from the recent literature; part two deals with experimental work suggested by this reconstruction; and part three attempts to evaluate the experimental results in terms of the known environmental factors, as well as to make some suggestions that may supply the information desired by Alling.

GEOLOGIC ENVIRONMENT OF THE CLINTON ORES.

Iron ores are found in rocks of Clintonian age in several states. In New York these rocks crop out in a long east-west band, and reach a maximum thickness of about 300 feet. The ore zones are long lenses

[1] An extended treatment of parts of the paper can be found in "The Mechanism of Replacement of the Clinton Iron Ores," by John R. Castaño, unpublished Masters Thesis, Northwestern University, 1950.

[2] Numbers in parentheses refer to Bibliography at end of paper.

ranging in thickness from a few inches to six feet. The chief ore mineral is hematite, with subsidiary chamosite (approximately $Fe_3Al_2Si_2O_{10} \cdot 2H_2O$).

The iron ores of the Clinton group were deposited in a very shallow sea (1, p. 1012). According to Gilette (5, pp. 70–71), all of the Clinton ores are directly associated with some major movements of the strand line. Not all the ores are connected with recession of the sea (as with the Walcott Furnace ore), but some, like the Furnaceville, are associated with positive movements of the shoreline. Gilette (5, pp. 70–71) adds that "it is easy to surmise that areas could be partly shut off either during an advance or retreat of the sea, since both would be associated with an oscillatory movement. In these isolated shallow basins iron ores apparently formed."

There is much evidence to substantiate the premise that deposition took place in shallow water. Newland and Hartnagel (12, p. 52) noted "extensive surface markings, cracks, and tracks of crustaceans and worms were found in shales and sandstones." Calcareous fossils were rounded and broken up by wave action. Both the quartz grains as well as the carbonate fossils that serve as nuclei for oolites are well rounded (1, p. 1010). Alling mentions that some quartz nuclei appear to have been rounded by chemical action caused by iron bearing solutions, but concludes that the rounding of clastic quartz is the result of mechanical wear. A. O. Hayes (7, p. 366) found raindrop impressions, mudcracks, and ripple marks in the very similar Ordovician Wabana iron ores of Newfoundland. He also noted (7, p. 366) that "they were laid down on a sea bottom that suffered continued oscillation relative to the surface of the water and in certain places were exposed above the tide during rainstorms." The same author held (8) that the ore was subject to oxidation either "in very shallow water or in lagoons in which the water level frequently fluctuated sufficiently to expose sediments to the air at intervals." In the Clinton it appears that some of the deposits may have been subject to subaereal erosion at times, but that this was not a necessary factor in ore formation.

Alling (1) considers that a succession of introductions and replacements were responsible for the ore. The iron was introduced by surface waters shortly after deposition and replaced a series of sedimentary minerals, chiefly carbonates, as part of the diagenesis of the rock. Alling used the term diagenetic replacement for this process. His work shows that these iron ores were originally limestones and were replaced by iron compounds, now largely hematite. Oolitic coatings consist of alternating thin layers of chamosite and hematite. The "fossil" ores contain nuclei of partially replaced calcareous fossils and subsequent oolitic coatings.

A. O. Hayes (8, p. 620) in his study of the Wabana iron ores of Newfoundland concluded that the "oolitic iron ore was an original sediment, and the hematite was formed before the consolidation of the rocks." The iron oxide, according to Hayes, may have been precipitated from sea water, or may have been the result of the oxidation of chamosite. If all the iron oxide is derived from chamosite, then more silica should be present than is actually the case. Hayes noted "the iron content of chamosite is not as high as that of hematite and that there is not enough silica nor alumina

now in the ores to satisfy the formula for chamosite" (1, pp. 1011–1012). Possibly some of the iron is derived from chamosite, but Hayes (8, p. 690) holds that "some of the hematite is secondary after chamosite, and some was precipitated directly."

From these observations and deductions arises a picture of a shallow well-aerated sea, alternating between deposition and fragmentation of calcium carbonate, perhaps associated with fall and rise of the strand line. The waters were clear and warm, and there were enough variations in bottom level to partially isolate individual basins. At irregular intervals iron was introduced, in some cases replacing fragmented calcium carbonate as hematite or being deposited directly as hematite; in places forming onion-shell layers of hematite and chamosite around nuclei of quartz grains or shell fragments; rarely being deposited as siderite. During these periods of iron addition, calcium carbonate deposition was not taking place; rather, as evidenced by the replacement of limestone and rounding of fossil fragments, it was being slowly dissolved. It is noteworthy that the iron addition was not accompanied by a rise in clastic content of the limestones.

It seems reasonable to presume that the iron was brought to such a strand by streams, and moved outward (or laterally) across a shallow water zone of limestone deposition. The mechanism by which the iron became separated from its usual accompanying clastics need not be discussed at the moment. The iron could have been carried colloidally, perhaps stabilized by organic matter, as suggested by Moore and Maynard (11), or conceivably as iron in true solution. The essential problem to be investigated (at least in terms of lack of information) seemed to be the latter possibility. What changes in total soluble iron take place when a stream enters an oceanic environment of well aerated waters with little accumulating organic material and abundant calcium carbonate present? To this end a highly idealized experiment was devised.

A river was simulated by a weak well-aerated solution of ferrous chloride; a "sea" by a sodium chloride solution containing solid calcium carbonate. The "river" was then introduced into the "sea," and observations made upon the resulting reactions. The two major variables measured were acidity (pH) and reduction-oxidation potential (*Eh*).

EXPERIMENTAL.

Reduction-Oxidation Potentials.—ZoBell (14) develops at length the theory of reduction-oxidation potentials, as well as methods of measurement and the relation of redox potentials to the character of marine sediments. Even more comprehensive treatment of the subject is given by Latimer (10) and Getman and Daniels (4). Derivation of the equations used here will be found in their work.

The redox potential (*Eh*) of a system is related to the standard electrode potential by the approximate equation:

$$Eh = Eo + \frac{RT}{nF} \ln \frac{(Ox.)}{(Red.)}, \qquad (1)$$

where Eh is the redox potential measured in volts, Eo is the standard electrode potential also measured in volts, R is the gas constant, T is the absolute temperature, n is the number of electrons involved, F is the Faraday, ln means natural logarithm, $(Ox.)$ is the concentration of the oxidized form of the couple, while $(Red.)$ is the concentration of the reduced portion of the couple.

The half-cell that is of prime interest in this study is the ferrous-ferric cell. The reaction may be written:

$$Fe^{+++} + e = Fe^{++}; \qquad Eo = 0.783 \text{ volt} \tag{2}$$

(Getman and Daniels, 1943, p. 438). In this case Fe^{+++} is the oxidized form in equation (1), Fe^{++} is the reduced form, and substituting in equation (1):

$$Eh = Eo + \frac{RT}{nF} \ln \frac{(Fe^{+++})}{(Fe^{++})}. \tag{3}$$

This equation, like equation (1) is only approximate; it becomes exact if the activity of the ions is substituted for the concentration. The relation between activity and concentration is defined by the equation:

$$a_i = \gamma_i m_i, \tag{4}$$

where a_i is the activity of a given ion, γ_i is its activity coefficient, and m_i is the concentration or molality. The activity and the concentration are measured in the same units, whereas γ_i is dimensionless. In the ferrous-ferric system that is of principal interest here:

$$a_{Fe^{+++}} = \gamma_{Fe^{+++}} m_{Fe^{+++}}; \qquad a_{Fe^{++}} = \gamma_{Fe^{++}} m_{Fe^{++}}. \tag{5}$$

Using activities instead of concentrations, equation (3) becomes exact:

$$Eh = Eo + \frac{RT}{nF} \ln \frac{a_{Fe^{+++}}}{a_{Fe^{++}}}. \tag{6}$$

If Briggsian logarithms are used instead of Napierian logarithms (utilizing the conversion factor $\ln x = 2.303 \log x$), then $\frac{RT}{nF} \ln x = 2.303 \frac{RT}{nF} \log x$. At 25° C, the coefficient of $\log x$ is a constant with a value of 0.06. Then equation (6) becomes:

$$Eh = Eo + 0.06 \log \frac{a_{Fe^{+++}}}{a_{Fe^{++}}}. \tag{7}$$

When the system is 50 percent oxidized and 50 percent reduced (when $a_{Fe^{++}}$ and $a_{Fe^{+++}}$ are equal), $Eo = Eh$.

EXPERIMENTAL PROCEDURE.

Preparation of the "Sea."—The artificial "sea" was prepared by dissolving enough crystalline sodium chloride in 500 ml of distilled water to make a 3.5 percent solution, approximating a normal ocean concentration of 35‰ salinity. The cylindrical vessel in which the solution was placed

was kept open to the atmosphere. In this way equilibrium with atmospheric oxygen and carbon dioxide was maintained, paralleling the conditions in shallow agitated waters. In the bottom of this cylinder was placed 85 grams of calcite, crushed to a size range of 0.5 to 0.71 mm, thus approximating actual fragment sizes in the Clinton deposits. The entire mixture was agitated by a motor stirrer that kept the bulk of the calcite in suspension. Stirring was continued until the pH of the "sea" became constant.

Prior to this, a similar solution had been prepared to test the effect of continued agitation on the roundness of the calcite grains.

Preparation of the "River Water."—A M/100 solution of ferrous chloride was prepared by dissolving 1.27 grams of the salt in a liter of distilled water. Air was bubbled through the solution until the *Eh* and pH values became constant.

Preparation of a Standard Redox Solution.—The standard redox solution mentioned by ZoBell (14, p. 495) was used as a periodic check on the measuring instruments used in the experiments. It was prepared by making a 250 ml solution of M/300 $K_3Fe(CN)_6$ and $K_4Fe(CN)_6$ in M/10 KCl. This solution has an *Eh* of 0.430 volt at 25° C.

Mixture of the "Sea" and the "River."—After both the "sea" and the "river" had come to equilibrium, 125 ml of clear, filtered M/100 ferrous chloride solution was added to the vessel containing the salt solution and the calcite. The mixture was mechanically stirred throughout the experiment. Samples of the mixture were withdrawn periodically to measure the pH and *Eh*. pH was measured with a Beckman Model G pH meter. The redox potential was measured with a setup similar to that shown by ZoBell (14, p. 493, Fig. 2). The electrodes were attached to a Leeds and Northrup portable potentiometer.

After the entire system had been brought to equilibrium, more sodium chloride was added to bring the salinity back up to 35‰. Then a second run was made using another 100 ml of the previously prepared M/100 ferrous chloride solution. Again, pH and redox values were measured at various intervals until equilibrium was reestablished.

At the end of the two runs, several hundred calcite grains were taken out of the "sea" and examined under the binocular microscope.

OBSERVATIONS AND RESULTS.

Reliability of Readings.—Both the pH meter and the redox setup were checked daily. The pH meter was checked with a standard buffer solution; the values should be reliable to 0.1 pH unit. The redox measuring setup was checked against the previously prepared standard solution before use each day. The standard *Eh* of this solution is 0.430 volt at 25° C (14, p. 495). The potential for saturated calomel half-cells (based on the standard hydrogen half-cell = 0) at different temperatures is cited by ZoBell (14, p. 495).

Temperature	15° C	20° C	25° C	30° C	37° C
Potential in volts	0.252	0.249	0.246	0.242	0.236

These values are then added to the actual potential (E) observed to get the *Eh* value for the system, for *Eh* refers to potential relative to a standard hydrogen electrode, rather than to a calomel electrode. For example, the emf reading on the potentiometer is 0.240 volt at 25° C. Then the emf reading and the potential for the saturated calomel half-cell are added, so that the actual *Eh* of the given system at that temperature is 0.486 volt. In equation form:

$$Eh \text{ (system being measured)} = E \text{ (observed)} + Eh \text{ (calomel half-cell)} \quad (8).$$

In the "sea" the temperature only varied from 24° C to 26° C during the course of the experiments. This small range, together with the fact that the system was rarely well enough poised[3] to give readings within ± 0.005 volts made it possible to add 0.246 volts to the measured potential to obtain the *Eh* of the system, and temperature effects could be neglected. Thus *Eh* values are accurate within approximately ± 0.005 volts.

Hydrogen Ion Concentration (pH) Readings.—Readings were made on the original sodium chloride solution at equilibrium. An hour after dissolving the salt the equilibrium pH was 5.6.[4] After the calcite was introduced into the system equilibrium conditions were attained within a few hours; equilibrium pH values ranged from 8.00 to 8.22.

Redox Potential and pH Measurements.—Before the ferrous chloride solution was introduced into the "sea," it was brought to equilibrium with the atmosphere by bubbling air through the solution. The equilibrium pH was 3.5; the *Eh* was 0.546 volt. Prior to the second run, the pH of the ferrous chloride was 4.0, whereas the *Eh* was found to be 0.536 volt. At these values of pH and *Eh* very little of the ferrous salt had been lost by hydrolysis to insoluble ferric hydroxide, as was evidenced by the small quantity of precipitate in colloidal suspension.

As mentioned previously, observations were made periodically on the pH and *Eh* of the system after the "river" was added. These relationships can best be shown graphically.

Figures 1 and 2 show the change of *Eh* and pH of the system with time, and Table 1 gives the measured values of pH and *Eh*. The *Eh* and pH curves have the same shape; a plot of *Eh* versus pH (Fig. 3) demonstrates that a linear relationship exists between these functions.

Precipitation of Iron Oxide and Rounding of Calcite Grains.—Shortly after mixing the solutions, the "sea" turned brown, owing to the precipitation of ferric oxide. As time went on, the "sea" cleared, and it was noted that the iron oxide precipitated in the bulk of the solution had settled to the bottom. At the end of the experiment the "sea" was clear, and lack of Tyndall effect indicated essentially complete coagulation of the originally very fine grained precipitate.

Before the "river" was introduced into the "sea," agitation of the "sea"

[3] "The capacity factor of a redox system is referred to as the *poise* and is analogous to the buffer capacity of a hydrogen-ion system" (14, p. 484).

[4] This low value may be attributed to the pH of the distilled water that was used, no attempt having been made to free it of dissolved gases.

Eh as a function of time for a "sea" and "river" mixture

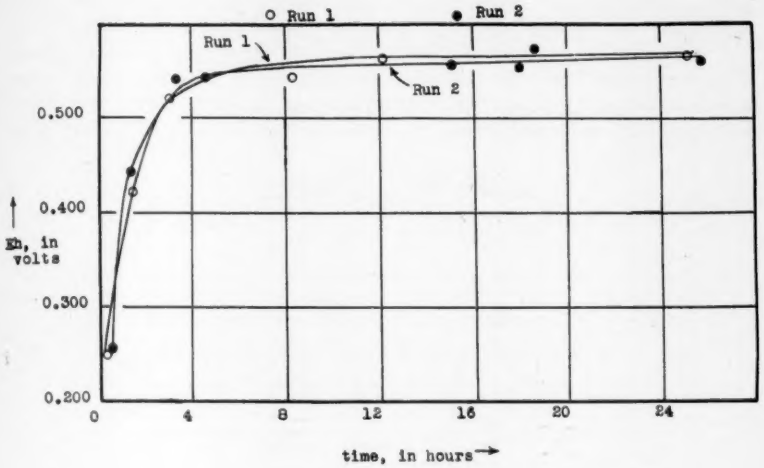


FIG. 1.

pH as a function of time for "sea" and "river" mixture

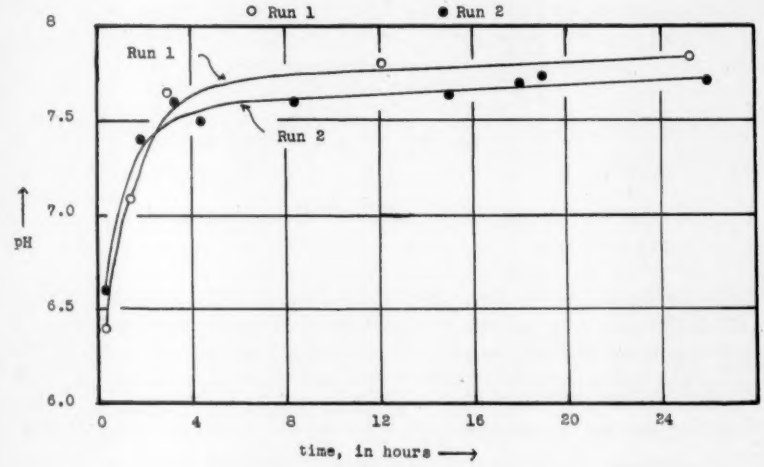
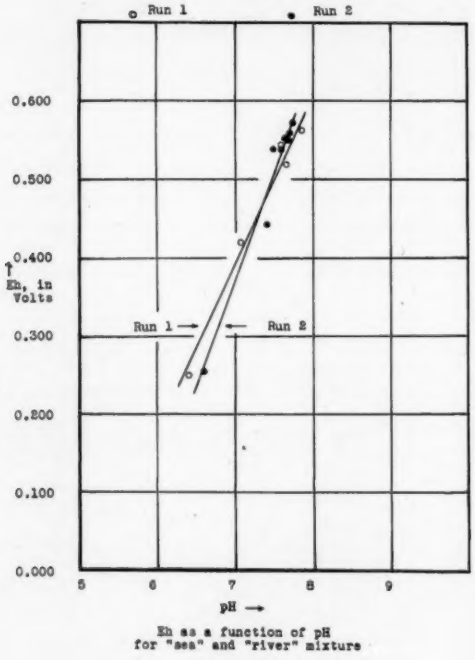


FIG. 2.

was maintained for eight days in an effort to determine the effect on the roundness of the calcite grains. It was found that very little rounding (if any) occurred during this period, for the average roundness of 209 grains was 0.104 [5] both before and after agitation. After the completion of run 2, the calcite grains were examined once more. Many grains were stained with iron oxide, and an increase in roundness was noted. This time, examination of 240 grains indicated an average roundness of 0.136. Average sphericity remained about the same throughout the experiment: 0.61



Eh as a function of pH for "sea" and "river" mixture

FIG. 3.

when first sampled, and 0.60 after equilibrium had been established after the second run. No increase in roundness took place after eight days of agitation when the "sea water" was in chemical equilibrium with calcium carbonate, but a noticeable increase was found after these grains had been in contact with the "river-sea" mixture. Thus it may be concluded that rounding was not accomplished by abrasion, but rather by chemical solu-

[5] The roundness and sphericity of the calcite grains were estimated with the aid of a visual chart devised by W. C. Krumbein (unpublished).

TABLE 1.

CHANGES IN pH AND *Eh* AS THE RESULT OF MIXING FERROUS CHLORIDE AND SODIUM CHLORIDE SOLUTIONS IN THE PRESENCE OF CALCITE (THE "RIVER" AND "SEA").

Elapsed time, hours and minutes	*E* Volts	*Eh* Volts	pH	Temp. °C
		Run 1		
Original $FeCl_2$ solution	0.300	0.546	3.5	25
0:25	0.005	0.251	6.4	24
1:35	0.175	0.421	7.08	24
3:00	0.275	0.521	7.65	24
8:20	0.300	0.546	7.6	25
12:03	0.320	0.566	7.8	24.5
25:12	0.318	0.564	7.85	24
		Run 2		
Original $FeCl_2$ solution	0.290	0.536	4.0	25
0:33	0.010	0.256	6.6	24
1:46	0.195	0.441	7.4	24
3:20	0.295	0.541	7.6	24
4:28	0.297	0.543	7.5	25
14:59	0.310	0.556	7.63	25
17:47	0.315	0.561	7.7	25
18:41	0.330	0.576	7.75	25
25:52	0.315	0.561	7.71	26

tion during the two ten-hour periods of attainment of equilibrium after mixing of the "sea" and the "river." Furthermore, solution of the grains was accompanied by simultaneous ferric oxide precipitation on them—a replacement process.

DISCUSSION OF EXPERIMENTAL RESULTS.

Calculation of the Activities of Ferrous and Ferric Ion.—The data on *Eh* and pH make it possible to calculate the maximum activities of ferrous and ferric ion in this system at any stage of the process of attainment of final equilibrium.

Control of Ferric Ion by Ferric Hydroxide Solubility.—The potential of a system containing both ferrous and ferric ions is given by equation (7). When this system is saturated with ferric hydroxide, the activity of the ferric ion, $a_{Fe^{+++}}$, is controlled by the hydroxyl ion, and consequently by the hydrogen ion activity (3, pp. 301–302). The activity product of ferric hydroxide is:

$$(a_{Fe^{+++}})(a_{OH^-})^3 = Ka_{Fe(OH)_3}. \tag{9}$$

If $Ka_{Fe(OH)_3}$ is denoted by S_1 then:

$$(a_{Fe^{+++}}) = \frac{S_1}{(a_{OH^-})^3}. \tag{10}$$

Also, from the ion product of water:

$$(a_{H^+})(a_{OH^-}) = Ka_w.$$

Then:

$$(a_{OH^-}) = \frac{Ka_w}{(a_{H^+})}, \quad \text{or} \quad (a_{OH^-})^3 = \frac{(Ka_w)^3}{(a_{H^+})^3}. \tag{11}$$

Substituting in equation (10):

$$(a_{Fe^{+++}}) = \frac{S_1(a_{H^+})^3}{(Ka_w)^3}. \tag{12}$$

Using this value of $(a_{Fe^{+++}})$ in equation (7):

$$Eh = Eo + 0.06 \log \frac{S_1(a_{H^+})^3}{(Ka_w)^3(a_{Fe^{++}})}. \tag{13}$$

Since S_1, Eo, and Ka_w are constants, it is convenient to define a new term E_0':

$$E_0' = E_0 + 0.06 \log \frac{S_1}{(Ka_w)^3}. \tag{14}$$

Then:

$$Eh = E_0' - 0.06 \log a_{Fe^{++}} - 0.174 \text{ pH}. \tag{15}$$

Equation (15) only requires that ferric ion be in equilibrium with ferric hydroxide; Cooper (3, p. 302) notes that the "Presence of other ions such as $Fe\,OH^{++}$ or $FeCl_6^{---}$ will have no effect."

The Relation Between the Activity of Ferrous Ion, Redox Potential, and pH. —Cooper (3, p. 304) has shown that if equation (2) applies, and the system is saturated with ferric ion but not ferrous ion, then equation (15) may be used. Eo is 0.783 volt (4); $(Ka_w)^3$ is $10^{-41.97}$; and $S_{1_{18°C}}$ is $10^{-38.6}$ (3). Substitution of these values in equation (14) gives:

$$E_0' = 1.00 \pm 0.05 \text{ volts}$$

and equation (15) becomes:

$$Eh = 1.00 - 0.06 \log a_{Fe^{++}} - 0.174 \text{ pH}.$$

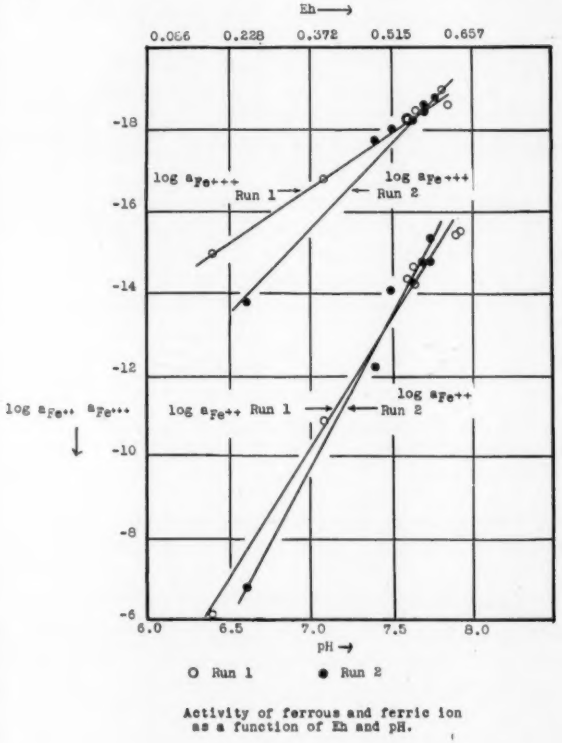
The validity of the equation can be checked from the experimental data. In the original M/100 ferrous chloride solution $a_{Fe^{++}}$ approximates 0.01 (neglecting $\gamma_{Fe^{++}}$). The measured Eh was 0.546 volt, and the pH 3.5. Letting E_0' be the unknown, and solving:

$$E_0' = -0.12 + 0.546 + 0.609 = 1.035 \text{ volt}.$$

A second check is obtained by calculating S_1 from equation (13). The value obtained is $10^{-37.5}$ at 25° C, as opposed to Cooper's value of $10^{-38.6}$ at 18° C.

With these checks of equation (15) the measured values of Eh and pH were substituted to obtain $a_{Fe^{++}}$ under the experimental conditions. Once $a_{Fe^{++}}$ has been determined, $a_{Fe^{+++}}$ may be calculated from equation (7). Table 2 presents the results of these calculations.

It is noteworthy that S_1 *is* a constant at all measured values of pH and *Eh*, showing that ferric ion was in equilibrium with the solid throughout the experiment. In other words, precipitation of ferric oxide "keeps up" with the changes of pH caused by the reaction of the acid "river" with the calcite of the "sea."



Activity of ferrous and ferric ion as a function of Eh and pH.

FIG. 4.

Relationship of the Activities of Ferrous and Ferric Ion to Eh and pH.— The calculated relationships of the activities of the various forms of iron are best shown graphically.

When log $a_{Fe^{+++}}$ and log $a_{Fe^{++}}$ are plotted as functions of *Eh* and pH, the resultant curves bring out the linear relationships between the variants (Fig. 4).

The ratio log $(a_{Fe^{+++}}/a_{Fe^{++}})$ (Table 2) indicates that the *proportion* of

TABLE 2.

MAXIMUM ACTIVITIES OF FERROUS AND FERRIC ION PRESENT IN THE "SEA." ACTIVITIES ARE IN MOLES PER LITER. S_1 EQUALS THE CALCULATED SOLUBILITY PRODUCT OF FERRIC HYDROXIDE.

Elapsed time, hours and minutes	pH	*E* (obs.) Volts	*Eh* Volts	$a_{Fe^{++}}$	$a_{Fe^{+++}}$	S_1	$\frac{a_{Fe^{+++}}}{a_{Fe^{++}}}$
Run 1							
Original $FeCl_2$ solution	3.5	0.300	0.546	$10^{-2.6}$	$10^{-6.5}$	10^{-38}	$10^{-3.9}$
0:25	6.4	0.005	0.251	$10^{-6.2}$	$10^{-15.1}$	$10^{-37.9}$	$10^{-8.5}$
1:35	7.08	0.175	0.421	$10^{-10.9}$	$10^{-16.9}$	$10^{-37.3}$	10^{-6}
3:00	7.65	0.275	0.521	$10^{-14.2}$	$10^{-18.6}$	$10^{-37.6}$	$10^{-4.4}$
8:20	7.6	0.300	0.546	$10^{-14.4}$	$10^{-18.4}$	$10^{-37.6}$	$10^{-4.0}$
12:03	7.8	0.320	0.566	$10^{-15.5}$	$10^{-19.1}$	$10^{-37.7}$	$10^{-3.6}$
25:12	7.85	0.318	0.564	$10^{-15.6}$	$10^{-18.7}$	$10^{-37.2}$	$10^{-3.1}$
Run 2							
Original $FeCl_2$ solution	4.0	0.290	0.536	10^{-4}	10^{-6}	10^{-38}	$10^{-2.0}$
0:33	6.6	0.010	0.256	$10^{-6.8}$	$10^{-13.9}$	$10^{-36.1}$	$10^{-7.1}$
1:46	7.4	0.195	0.441	$10^{-12.2}$	$10^{-17.9}$	$10^{-37.3}$	$10^{-5.7}$
3:20	7.6	0.295	0.541	$10^{-14.3}$	$10^{-18.3}$	$10^{-37.5}$	10^{-4}
4:28	7.5	0.297	0.543	$10^{-14.1}$	$10^{-18.1}$	$10^{-37.6}$	10^{-4}
14:59	7.63	0.310	0.556	$10^{-14.7}$	$10^{-18.3}$	$10^{-37.3}$	$10^{-3.6}$
17:47	7.7	0.315	0.551	$10^{-14.9}$	$10^{-18.7}$	$10^{-37.6}$	$10^{-3.9}$
18:41	7.75	0.330	0.576	$10^{-15.4}$	$10^{-18.9}$	$10^{-37.6}$	$10^{-3.5}$
25:52	7.7	0.315	0.561	$10^{-14.8}$	$10^{-18.5}$	$10^{-37.4}$	$10^{-3.7}$

ferric ion in solution in the "sea" increases with the passage of time; the ferrous-ferric ratio becomes constant in solutions with high *Eh* and pH values.

SUMMARY OF EXPERIMENTAL RESULTS

1. A well aerated solution of ferrous chloride is acid. Although it may contain fairly high concentrations of ferrous iron, and has a very high ferrous-ferric ratio, it is in equilibrium with solid ferric oxide.
2. A 3.5% aerated sodium chloride solution in equilibrium with solid calcium carbonate has a pH of approximately 8.0—within the range of ocean waters.
3. When the two solutions are mixed, the following changes occur:
   a) The pH of the mixture is intermediate on first mixing, but slowly returns to that of the original "sea." This restoration of high pH can be attributed to the "buffering" action of the solid calcium carbonate.
   b) The *Eh* of the mixture rises from an originally low value (0.250) to a final high value of about 0.560.
   c) With these changes in *Eh* and pH, the ferrous-ferric ratio decreases, and ferric oxide precipitates until at equilibrium

both ferrous and ferric ion are reduced to insignificant quantities.

d) The ferric oxide precipitates both in the bulk of the solution and as films on the calcite grains.

e) The calcite grains round appreciably by solution during the period of low pH values. The rate of rounding is very rapid compared to that produced by strong mechanical agitation.

APPLICATION OF EXPERIMENTAL WORK TO THE IRON ORE PROBLEM.

Validity of the Simple Experimental Model.—According to Cooper (3) the oxidation-reduction potential in sea water ranges between 0.43 and 0.75 volt, and is dependent only on the partial pressure of oxygen and the pH of the sea water. Furthermore, *Eh* is not particularly sensitive to changes in the amount of dissolved oxygen: reduction to as little as 10 percent of that in equilibrium with the atmosphere changes the *Eh* only 0.02 volt. Only when oxygen is removed essentially completely (as by organisms or organic material in poorly aerated waters) is there a major change in *Eh*.

ZoBell (14, p. 505) reports on studies made by Brujevich on well aerated, brown, oxidized sediments, rich in iron and manganese, on the floor of the Barents and Kara Seas. Brujevich found that the redox potential ranged from 0.105 to 0.250 volt; the corresponding range in pH was 6.7 to 8.3.

The present studies were conducted on a system that was well aerated; the equilibrium *Eh* values were in the vicinity of 0.550 volt, with equilibrium pH of about 7.8.

It can be concluded that the potentials measured in these experiments offer a valid approximation of the potentials that actually exist in well aerated sea water free from organic matter. Consequently, the model actually gives a check on the validity of previous theoretical calculations of iron content of sea water, for the experimental values of *Eh* and pH yielded an activity product of ferric hydroxide consistent with the accepted value determined from free energy relations.

Presumed Relations in the Clinton Sea.—On the basis of the experimental work, a fairly consistent hypothesis for the origin of the Clinton ores can be erected. It is not necessarily *the* explanation of the conditions of formation of the ores, but it provides at least a framework for discussion.

If rivers of moderately low pH drained into the Clinton sea, they might well contain considerable quantities of ferrous iron. Shelford (13) has shown that river water pH varies considerably, but that some rivers have values of 7.0 or slightly lower. On reaching the sea, the river would drop its clastic load. If it entered an area of open ocean circulation, the iron probably would be precipitated immediately, and diluted by the clastics, but if, instead, the river debouched into a lagoon or other zone of impeded circulation, river volume might be sufficient to keep the lagoonal or basin waters fairly fresh or at most brackish. In this case the clastics would be dropped, but the iron might be by-passed to a place where there was suffi-

cient ocean water in equilibrium with calcium carbonate to oxidize and precipitate the iron. It has been shown previously that the actual basins of iron ore deposition fit the picture, with their fragmental calcium carbonate and other evidences of wave action and consequent good aeration. The iron bearing solutions would then precipitate the iron as ferric oxide, and, if the experimental work is a guide, the iron oxide would replace the calcium carbonate as well as precipitate freely in the water.

Such conditions would not be expected to last very long; movements of the strand line might well put a given basin beyond the range of iron, and calcium carbonate deposition might be resumed. Also, change in river volume or silting up of a clastic-trapping basin might result in the more common precipitation of the iron along with the clastics.

SOME INFERENCES CONCERNING SPECIFIC PROBLEMS.

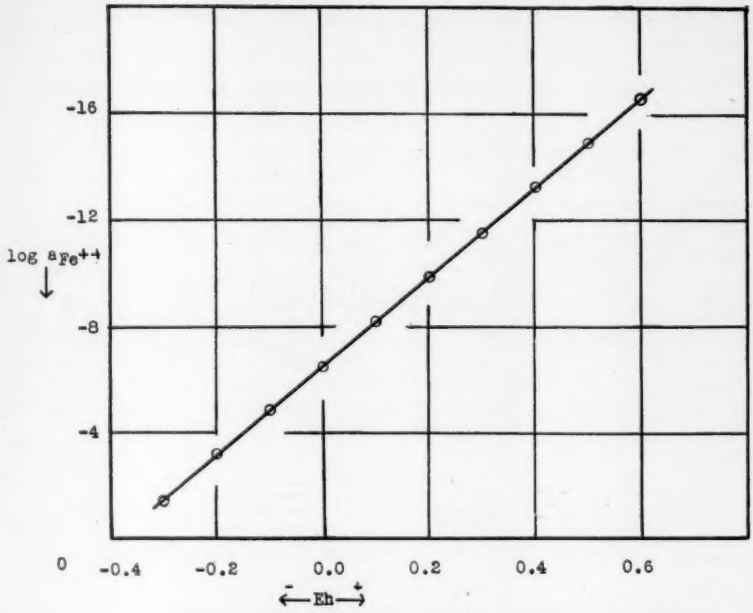
Colloidal versus Solution Transport of Iron.—The present work does not resolve the controversy concerning colloidal transport of iron versus solution transport. However, there are two points that should be mentioned in favor of the solution hypothesis. The environment of the Clinton ores is one that would be expected to act as a precipitant for iron in solution, whereas there is no information concerning a specific effect of aerated calcium carbonate bearing waters on colloidal coagulation. Second, the solution hypothesis provides a mechanism for replacement of the calcium carbonate.

Hematite-Chamosite-Siderite Relations.—This discussion becomes highly speculative when an attempt is made to explain detailed mineral relations, but a certain amount of such discussion may be a useful guide in collection of further data.

A common occurrence is the alternation of hematite-chamosite onion-skin layers in oolites. Chamosite is a ferrous aluminum silicate; it is suggested that with increase in the amount of fresh water passing into the marine basin that the pH would be slightly lower, increasing the ferrous ion concentration, and that more silt would be expected to move in, providing a source of aluminum. It is conceivable that such conditions might be seasonal. For example, Cooper (2) has shown that diatom tests in the English Channel may be almost completely dissolved seasonally, and suggests a correlation with changing pH values related to seasonal fluctuation in river flow.

Siderite occurs rarely in the ores. It must depend for its formation on the activity of ferrous ion and the activity of carbonate ion. Optimum conditions would be at fairly low pH values, where activity of ferrous ion is a maximum, whereas hydroxyl ion is relatively low. Both hydroxyl and carbonate ion concentrations increase with increasing pH, but since the precipitation of hematite depends on the cube of the hydroxyl ion, and ferrous carbonate on its square, increase in pH would favor the formation of hematite.

In well oxygenated waters a tentative sequence can be set up with increasing pH—siderite-chamosite-hematite. Obviously aluminum concen-



Activity of ferrous iron as a function of Eh with pH constant (8.0). This graph illustrates the effect of reducing materials (i.e. organic matter) on a basin of iron deposition.

FIG. 5.

tration will influence the formation of chamosite, but in the presence of silt, the above relation might hold.

The Effect of Organic Material.—The Clinton environment, consisting of agitated and aerated waters, provided conditions adverse to the preservation of organic material. In other environments, where organic material is preserved, there will be major differences in the ferrous-ferric relations. ZoBell (14) shows that marine sediments with appreciable organic content have low *Eh* values. Where organic debris and stagnant water coexist, oxygen is rapidly removed. Iron moving into such an environment would certainly tend to precipitate as ferrous compounds. In the presence of organic matter, siderite, chamosite, or perhaps pyrite would be expected to form. Figure 5 shows the effect on ferrous ion activity of decreasing *Eh* values. The calculation was made at constant pH of 8, for many marine sediments have pH values near 8. The presence of hematite in the Clinton ores, and relatively low content of pyrite or siderite, supports the inference

that the environment had open circulation, and that organic matter was destroyed as rapidly as it was formed.

SUMMARY.

Very broadly, it can be stated that iron bearing solutions moving into aerated ocean waters containing calcium carbonate will precipitate ferric oxide; with addition of silt and perhaps a slight lowering of pH they may be expected to precipitate chamosite. If, however, they move into an area of stagnant water where organic debris tends to accumulate, the minerals formed might well be chamosite (if silt is present) or siderite and pyrite.

ACKNOWLEDGMENTS.

The authors are indebted to Dr. W. C. Krumbein of Northwestern University for his continued interest in the problem, and his many helpful discussions and criticisms. Professor Harold L. Alling of the University of Rochester read the manuscript and we benefited greatly from his comments. We have incorporated his suggestions into the manuscript to the best of our abilities.

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MANGANESE ON PUNTA CONCEPCION, BAJA CALIFORNIA, MEXICO.

JAMES A. NOBLE.

ABSTRACT.

On Punta Concepcion in Baja California, a group of volcanic rocks of Miocene age is intruded by igneous rocks of the same age, and both are overlain unconformably by lower Pliocene sedimentary rocks of nonmarine and marine origin. Veins of pyrolusite and other minerals are abundant in some basalts of the volcanic series and also cut the intrusives and the lowermost lower Pliocene rocks but form detrital grains in other members of the lower Pliocene series. The veins of almost pure pyrolusite are very narrow but very rich and locally abundant. They provided a small supply of chemical grade ore during World War II. The veins are believed to be of primary hydrothermal origin.

INTRODUCTION.

PUNTA CONCEPCION is a peninsula jutting northward into the Gulf of California from the east side of the larger peninsula of Baja California (Fig. 1). Both sides of Baja California carry a number of these barblike northward projecting peninsulas, flanked by bays opened by the strong northwest storm winds. Punta Concepcion is flanked by Concepcion Bay on the west side and by the Gulf of California on the east side. The nearest well known shipping point is the port of Guaymas, to the northeast across the Gulf on the mainland, about 145 kilometers away. The port of Santa Rosalia and the copper mine of El Boleo are about 25 kilometers along the coast to the north, and the small port of Mulegé is directly across Concepcion Bay about 5 kilometers away. The climate of the district is extremely arid, and in some years there is no rainfall; hence there is scarcely enough fresh water for domestic use of the meager population. The manganese deposits occur at the sea shore and extend under the water for unknown distances.

The occurrence of manganese ore on Punta Concepcion has been known for many years,[1] and during World War I a small tonnage of ore was sorted from beach cobbles. The deposits were opened by mining work early in World War II, and a moderate tonnage of chemical grade ore was uncovered and shipped. The property was then purchased by the Compañia Mexicana de Manganeso, and the ore shipments were increased considerably. As exploration work proceeded, it became evident that a large tonnage of low grade ore

[1] Halse, Edward, Notes on the occurrence of manganese ore near Mulegé, Baja California, Mexico: North of England Inst. Min. Mech. Eng. Trans., vol. 41, pp. 302–307, 1892. Wallace, H. V., Deposits of manganese in Lower California: Min. World, vol. 35, pp. 103–104, 1911. Wallace, H. V., Informe sobre los depósitos de manganeso cerca del pueblo de Mulegé, Baja California: Bol. Minero (Mexico), vol. 1, pp. 209–212, 1916. McQuesten, C. A., Minas de manganeso en Punta Concepcion, Municipalidad de Mulegé, Baja California: Bol. Minero, vol. 1, pp. 232–235, Mexico, 1916.

could be blocked out and mined by cheap methods. Preliminary tests indicated that good milling recoveries could be made in spite of many handicaps, but subsequent operations presented many difficulties, and after the close of hostilities a profitable operation of large scale mining and milling could not be maintained. The exploratory work and mining operations did serve, however, to provide details of the areal geology and stratigraphy of a little known part of Mexico and to give information on an unusual type of manganese ore.

Three groups of rocks make up the north end of Punta Concepcion. The oldest is an extrusive series of volcanic rocks, agglomerates, tuffs, and basalts, and one or two beds of conglomerate. The next younger group is composed of intrusive basalts and diorites which cut the extrusive series and occupy large areas along the axis of the peninsula. The third group of rocks is predominantly sedimentary in origin, mainly terrestrial conglomerates or fanglomerates

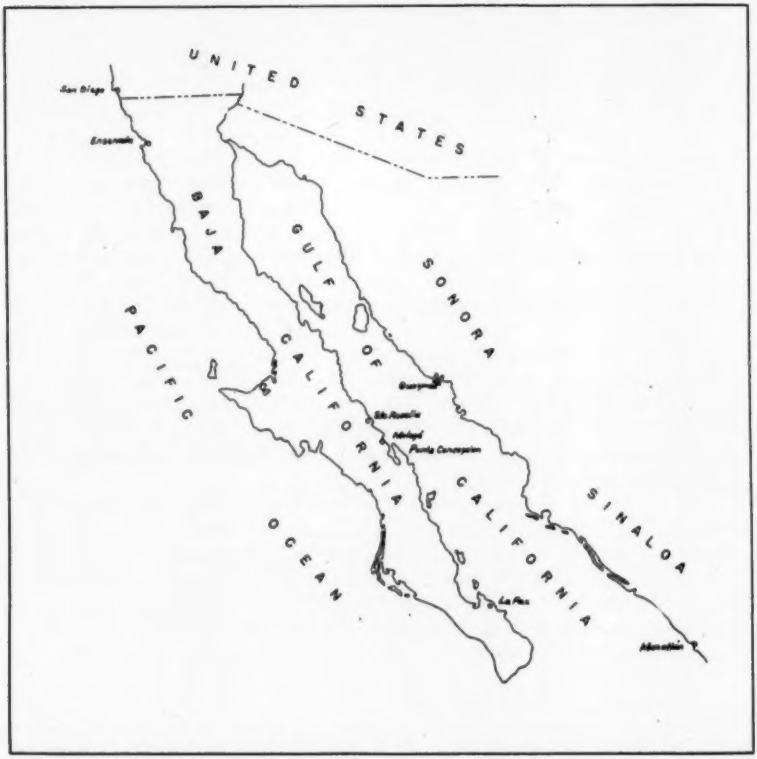


FIG. 1. Location of Punta Concepcion in relation to other geographic features of Mexico.

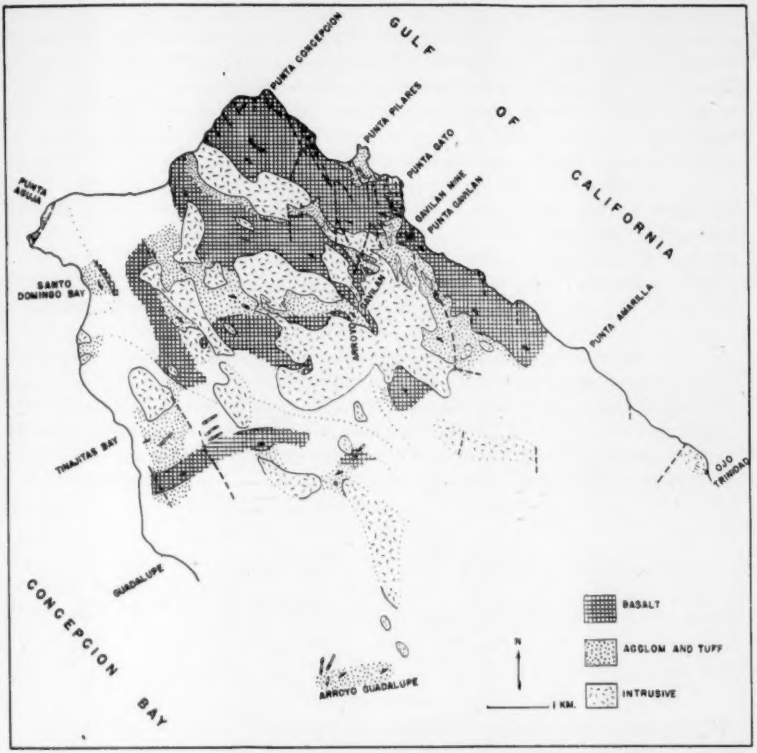


FIG. 2. Distribution of the extrusive and intrusive rocks (Comondú formation) on Punta Concepcion.

with some tuff beds and one bed of marine shells. The sedimentary series lies unconformably on the rocks of the two older series and forms a discontinuous fringe around the margins of the peninsula. The two older series, the extrusive rocks and the intrusive rocks, have generally been grouped, in earlier published papers on the geology of Baja California, under one name, the Comondú Series, to which a Miocene age is commonly assigned. The youngest group, the sedimentary series, correlates with the series known as the Boleo formation at Santa Rosalia, of lower Pliocene age.[2]

The geologic history of the peninsula is characterized by long-continued faulting, and the area may be an extension of the basin and range topographic province of the western United States. Great thicknesses of dark agglomerate

[2] Wilson, I. F., and Veytia, Mario, Geology and manganese deposits of the Lucifer district northwest of Santa Rosalia, Baja California, Mexico: U. S. Geol. Survey Bull. 960–F, pp. 177–233, 1949.

with monoclinal northwest dips occupy the west side of the peninsula, whereas a heterogeneous assemblage of lighter colored agglomerates, tuffs, and basalts occupy the east side and dip northeast, nearly at right angles to the first series. All the rocks are cut by many later faults which for the most part strike a little west of north. The general shape of the Gulf of California apparently was established before the period of deposition of the sedimentary series, but Concepcion Bay probably was developed by faulting during that period or at its close. Relatively recently the peninsula has been uplifted and probably tilted, and this uplift and tilting may have coincided with the downfaulting of the bay. Raised beaches occur at several horizons, the most conspicuous being one at about 21 meters above high tide.

A period of mineralization resulted in the deposition of calcite, pyrolusite and other manganese oxide minerals, and small amounts of other minerals. Countless veinlets of pure pyrolusite cut the basalts and make minable ore wherever the spacing of the veinlets is close enough. The products of mineralization are rather widely distributed. In detail they are guided by faults, and they cut all the rocks except the latest members of the sedimentary series; but clastic grains of pyrolusite in the Pliocene marine shell bed show that mineralization had taken place by that time. The manganiferous veins seem to be primary products of hydrothermal mineralization.

EXTRUSIVE SERIES.

The distribution and structure of the extrusive rocks are shown on Figure 2. The sequence of extrusive rocks has been most carefully studied near the line of an auto road from the head of Arroyo Gavilan to the Gavilan mine and in the vicinity of the mine. The rock exposures are exceptionally good, but some of the outcrops are separated by wide areas of intrusive rock. The detailed sequence is as follows:

18. Basalt—16 meters plus
17. Basalt—27 meters
16. Basalt—15 meters
15. Basalt—7½ meters
14. Basalt—35 meters plus
13. Basalt—28 meters
12. Coarse tuff with pebbles—10 meters
11. Tan tuff with some pebbles—38 meters
10. Tan conglomerate—40 meters
9. Gray tuff—35 meters
8. Basalt—20 meters
7. Tan tuff—35 meters
6. Basalt—35 meters
5. Tan tuff—30 meters
4. Basalts—200 to 300 meters
3. Light colored tuff—125 meters
2. Basalt—70 meters (more?)
1. Light tan tuff—35 meters.

The sequence changes along other lines of measurement, and the beds can be seen to change in thickness and character along their strike. The basalts numbered 13 to 18 inclusive carry the ore in the mine area. Bed 13, because of a minor unconformity, rests on successively older beds to the northwest of the mine area. The conglomerate bed number 10 becomes much thicker south of the mine, where it is many hundred meters thick. Some of the tuffs when traced to the northwest become quite red, resembling redbeds. Northwest of the road a thick lens of agglomerate appears between beds 2 and 3.

The basalts of the mine series (beds 13 to 18 inclusive) have been studied under the microscope. They consist of labradorite, green augite, olivine, and iron oxides. All have labradorite and olivine phenocrysts, and some, but not all, have augite as well. Groundmasses are fine grained and consist of plagioclase, augite, and iron oxides.

The rocks on the west side of the peninsula, along Concepcion Bay, though not as carefully studied, do not correspond closely with the sequence described above. Excellent exposures in Arroyo Guadalupe show a great thickness of rather dark agglomerate, with only a few narrow beds of tuff and basalt; similar sequences have been noted in adjacent arroyos.

In addition to a difference in lithology between the eastern and western sides of the peninsula, there is a marked difference in attitudes of the beds. On the east side of the peninsula the rocks strike northwest and dip northeast, steeper (up to 50 degrees) in the high part of the peninsula and as flat as 20 degrees along the coast. Near Punta Concepcion the dips are very low but strikes are still to the northwest, except for one area where the beds are practically flat. On the west side of the peninsula, on the other hand, the extrusive rocks strike northeast, nearly at right angles to the strikes of the opposite side of the peninsula, and they dip 15 degrees to the northwest. Much reconnaissance mapping failed to support a hypothesis that these two groups of rocks are separated by a fault, and the most reasonable explanation for the discordance in strike is that the two groups are separated by a sharp fold, with the sequence of the eastern side overlying that of the western side.

At the place called El Salto, about 20 kilometers south of the mine and beyond the limits of the map, coarse agglomerates with interbedded tuffs and basalts like those of the west side of the peninsula overlie coarse crossbedded red sandstones which probably correlate with rocks mapped elsewhere in Baja California under the name Isidro formation. This formation is believed to be of Lower Miocene age.[3] A small angular unconformity appears to separate the two groups.

On Punta Los Pilares, about a kilometer north of the mine, the volcanic rocks are highly folded and faulted, and contain several additional sedimentary members as well as some very coarse intrusive breccias. There is some suggestion that this area is part of a volcanic vent, set off from the surrounding volcanic and sedimentary material by a subcircular network of faults, but with some sedimentary members continuing into the center of vulcanism with change of facies.

[3] Durham, J. W., *in* Weaver, C. E., et al., Correlations of the marine Cenozoic formations of western North America: Geol. Soc. America Bull., vol. 55, p. 575 and chart 11, 1944.

INTRUSIVE ROCKS.

The distribution of the intrusive rocks is shown on Figure 2. Intrusive rocks cover much of the area of the peninsula and may be even more abundant than is shown on the map, because they are not easily distinguished from the extrusive rocks. The distribution of the intrusive rocks suggests a zone of intrusive bodies striking northwest along the axis of the peninsula, and some of the larger intrusive bodies also strike about northwest. Many of the bodies are, however, decidedly irregular in shape. In most places the contacts of the intrusive rocks with the enclosing volcanic rocks seemed to be nearly vertical; but some intrusive bodies are sills, and a few bodies have nearly vertical contacts on one side and gently dipping conformable contacts on the other side. A few narrow dikes were noted. Most of these strike about northeast, transverse to the general trend of the intrusive zone, and are about vertical.

On fresh exposures most of the intrusive rocks are dark gray and are rather fine grained but have phenocrysts of feldspar and augite, and they are hard enough to make rather prominent outcrops. Some are reddish gray or red, and a few are light gray. On weathered surfaces various shades of red or reddish brown predominate, and one type of rock weathers to purple. Quite a number of the intrusive rocks are vesicular and amygdaloidal, and some show rather prominent flow banding. It has not been possible in some places to distinguish intrusive rocks from extrusive ones, but many of the intrusive rocks show marked differences and can be mapped with confidence. Probably many small intrusive bodies have been missed in the mapping.

Fifteen specimens of intrusive rock have been studied under the microscope. All the specimens but one came from the intrusive bodies exposed in Arroyo Gavilan and its tributaries, and one specimen came from a dike about one kilometer away. The microscopic study shows both basalts and diorites. In the basalts, phenocrysts are plagioclase and augite and in most rocks olivine; groundmasses are composed of plagioclase and augite, the latter generally conspicuous. The plagioclase phenocrysts seem to have an appreciable range of composition in each specimen but are mostly labradorite with a little andesine in some specimens. In the diorites, phenocrysts are plagioclase and augite, and groundmasses are plagioclase or plagioclase and augite, and some specimens have iron oxides. The plagioclases again show an appreciable range in composition in each specimen, but most fall within the limits of andesine, with a few calcic oligoclases and a few sodic labradorites. Groundmasses in the diorites are rather more fine grained than in the basalts, and some show glass. One diorite, light gray on the fresh outcrop and purple on weathered surfaces, had a very little quartz among the phenocrysts and in the groundmass, the total amount being well under 5 percent. No other specimen showed any quartz.

The narrow dikes showed no compositional or textural differences from the larger intrusive rocks.

A few bodies of intrusive breccia have been mapped. These seem to be made up of fragments of rocks like those already described, but they have not been studied in detail.

For the most part the intrusive basalts cannot be distinguished from extrusive basalts either in hand specimen or under the microscope. This fact suggests that the rocks were intruded under very light cover and that some of the intrusive bodies may have been feeders for some of these flows or others like them. No andesite, the extrusive equivalent of diorite, has been mapped, and if any of the diorite bodies represent vents the extrusive material is either among the agglomerates or tuffs, or it was extruded beyond the area of this map.

SEDIMENTARY SERIES.

The distribution and structure of the sedimentary series are shown in Figure 3. The rocks grouped under the name of sedimentary series are of great interest because of the light they throw on the more recent geologic history of the

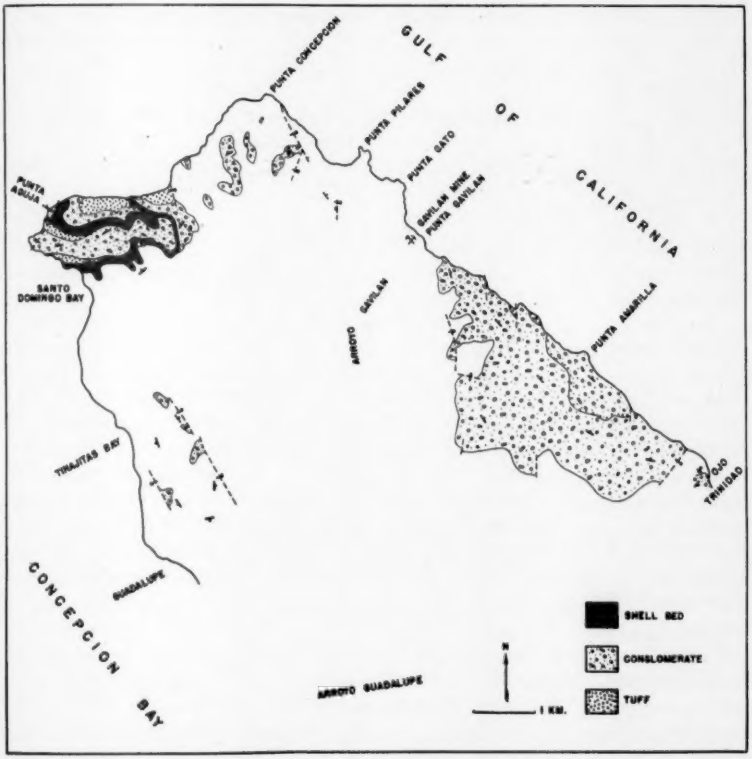


FIG. 3. Distribution of the sedimentary rocks (Boleo formation) on Punta Concepcion.

area, and also because they date the period of ore deposition, the earlier members of the series being older than the ore and the younger members being later than the ore. A bed of marine shells provided fauna which proved to be correlated with the Imperial formation (lower Pliocene?).[4]

The rocks of the sedimentary series occur in two large areas, one at Punta Amarilla, southeast of Punta Gavilan, and the other at Punta Aguja, and also in smaller scattered spots along the coast on both sides of the peninsula. The conglomerates of this series also continue along the coast southeast of Ojo Trinidad for several kilometers.

Because of the rapid change in character of the rocks from one area to another, the stratigraphy of this series can be presented best in a tabular form.

Punta Amarilla	Punta Concepcion	Punta Aguja	Tinajitas Bay
		5 Tan congl. 4 Tan tuff* 3 Shell bed unconf?	1 Tan congl. (with a little tuff and shells at base)
3 Green congl. 2 Yellow tuff 1 Tan congl.	1 Tan congl.	2 Tan congl.* 1 Yellow and brown tuff*	

* Missing in part.

In each area the lowest beds rest unconformably on the rocks of the extrusive series or on intrusive rocks. It was not possible to measure the thicknesses of the formations, which change greatly from place to place. Most of the series is made up of a light tan conglomerate which consists of fairly large partly rounded boulders and cobbles of a variety of igneous rocks set in a matrix of smaller pebbles of similar material and a considerable amount of tuff. This conglomerate erodes into steep cliffs and makes an area of very precipitous topography between the mine and Ojo Trinidad. In that area an upper member is faintly greenish, the color being due to an abundance of greenish tuff in the matrix. This upper conglomerate is separated from the lower one by a few meters of yellow tuff. Scattered areas of tan conglomerate near Punta Concepcion rest unconformably on extrusive and intrusive rocks and probably correlate with the lower conglomerate of Punta Amarilla. Several new members appear near Punta Aguja, however. What seems to be this same tan conglomerate is underlain along the coast by yellow sandy tuff, and that in turn is underlain by light brown tuff. Over the tan conglomerate is a shell bed of striking character, containing almost no detrital material and composed almost wholly of marine shells of several varieties of pecten and a few other pelecypods and some gastropods. There are some detrital grains of pyrolusite. This bed is from 6 to 10 meters thick. Where it reaches the shore in Santo Domingo Bay, I. F. Wilson collected the material previously cited as correlating with the Im-

[4] Wilson, I. F., Personal communication, quoting Vokes, H. E.

perial formation. In places the tuffs and conglomerates are missing, and the shell bed rests directly on extrusive and intrusive rocks. Over the shell bed is a discontinuous bed of light tan tuff, and over that (resting on the shell bed in part of the area) is tan conglomerate, the highest exposed member of the series. Along the shore east of Punta Aguja the deposits are light tan conglomerates with a little tuff and marine shell beds at the base in places. Probably the shell beds correlate with the one at Santo Domingo Bay and the conglomerate with the upper conglomerate of that area.

In all probability the conglomerates which make up most of this series were deposited on a gently sloping surface which extended seaward from a mountain range of igneous rocks. In the conglomerates there is almost no evidence of water sorting. The facies changes suggest that the coarse thick conglomerates inland from Punta Amarilla and also farther southeast beyond the map area are not far from their original source, and that the mountain range from which they were derived stood about along the present axis of the peninsula. There is no indication of the proximity of the shore line; presumably it was some distance outside its present location. Toward Punta Concepcion the cobbles of the conglomerate are somewhat finer and had travelled farther from their original source. Only a few troughlike remnants remain here. Farther to the west, near Punta Aguja, the tuffs which underlie the conglomerate occupy a depression between two faults, suggesting that these tuffs were once more extensive, perhaps covering the whole area, and were removed by erosion except where they were protected in the fault depression. The thinning of the conglomerate and the overlap of the shell bed across the conglomerate onto the older rocks indicate the first transgression of the sea onto the map area, presumably within the limits of the still sinking fault depression. The outcrops near Tinajitas Bay were probably just on the edge of the body of water. The submergence seems to have lasted only a brief time and was succeeded by emergence and the accumulation of more conglomerates.

The rocks of the sedimentary series have suffered a considerable amount of deformation. Faulting is fairly common, and in places the beds have been gently folded. Assuming that the conglomerate was laid down on a moderately sloping surface with only minor irregularities, as seems most probable, the deformations which have taken place subsequently are seen to have produced a broad domal uplift in the vicinity of the mine area. This uplift was produced partly by folding but mainly by faults which strike a little west of north. The downfaulting near Punta Aguja has already been described. There, one fault strikes a little west of north, the other east of north. The area near Tinajitas Bay is a slightly domed block which has been dropped down in a fault trough between faults which strike west of north. The relations at Punta Aguja, discussed above, and the relations of the manganese mineralization to the rocks of the sedimentary series and to the faults, to be discussed later, show that the faults which strike west of north (and perhaps some others as well) were first formed before the period of deposition of the sedimentary series but continued to produce displacement after that period.

MORE RECENT MOVEMENTS.

The development of Concepcion Bay is thought to be still more recent than the deformations just described and was a result of downfaulting in a trough similar to that which localized the marine sediments near Punta Aguja. Unconsolidated gravel deposits, probably fluviatile in origin, make up much of the coast line of Concepcion Bay southeast from Santo Domingo Bay, for several kilometers to the southeast. The stream courses between Tinajitas Bay and Guadalupe, and others to the southeast, spread out and disappear on alluvial fans, whereas elsewhere on the map area stream beds run directly into the sea with no accumulation of gravel in the lower courses except small storm built ridges near the shore line. These alluvial fans are being eroded by storm waves now and once extended beyond the present shore line. Presumably they rest on a suballuvial bench and were deposited in an aggrading basin during a period of rising base-level, the basin being subsequently invaded by the sea to form the present Concepcion Bay. Possibly these alluvial fans formed during Pleistocene time when the general sea level was appreciably lower because of world-wide loss of sea water due to continental glaciation.

Near the shore line southeast from Punta Concepcion there are remnants of two marine benches which indicate recent emergence of the land. The older, higher bench is well preserved between Punta Concepcion and Punta Los Pilares. The surface of the bench here slopes down to the northeast at about 6 degrees and is cut off at the shore line by a vertical sea cliff about 25 meters high. A somewhat lower bench is well exposed on most of the headlands southeast from Punta Los Pilares. In most places it has a flatter slope than the higher bench and ends along the shore in a vertical sea cliff about 10 meters high. The head of this bench is about 21 meters above high tide in the mine area but is somewhat lower farther south. The surfaces of both benches carry a very thin veneer of well rounded pebbles and scattered deposits of marine shells and precipitated lime carbonate.

The 6-degree slope of the upper bench when projected inward away from the sea coast is seen to pass above the high topography in the center of the peninsula. No remnants of a bench corresponding to this have been found on the other side of the peninsula, along the shores of Concepcion Bay. It seems probable that the bench was once continuous and more nearly level across the present site of the peninsula, and that uplift and tilting have permitted stream erosion to remove all but the few remnants now left along the northeast edge of the area. Whether the lower bench gives evidence of a similar regional tilting was not determined, but warping to the amount of 2 or 3 meters was detected.

The downfaulting which eventually produced Concepcion Bay and this uplift and possible tilting of the peninsula may have taken place together. If so, the process is an example of basin and range faulting, in this case the basin having been subsequently drowned by the sea. The age of the faulting is probably later than lower Pliocene and is probably Pleistocene. But faulting of the 21-meter bench in the mine area shows that faulting was resumed or has continued in very recent time.

Although there is thus reason to believe that Concepcion Bay is a result of faulting, there is no evidence that the strikingly rectangular shape of the peninsula is a direct result of faulting. The two shore lines extending southeast and southwest nearly at right angles from Punta Concepcion are on the whole remarkably straight, minor irregularities being related directly to differences in hardness of rocks or to small faults. Neither the geologic history nor the geologic map suggests, however, that large faults have had any part in shaping these shore lines, nor are there any faceted spurs so characteristic of fault-line scarps elsewhere. The recent movements seem to have been epeirogenic uplifts probably accompanied by tilting up to the southwest; the whole area of the peninsula has been lifted, but the southwest side has been raised higher. Probably a fault delimited the southwest side of the uplifted block, but there is no necessity for a fault on the northeast side and no suggestion, in the pattern of small faults, that a major fault outlined the northeast coast. The nearly straight shore lines seem to be the result of the attack of storm waves on a raised and tilted marine bench.

There has been discussion in recent years of the significance of horizontal wave-cut rock platforms that occur between the limits of high and low tide in many parts of the Pacific Ocean.[5] Some authors have held these to be evidence of recent emergence of a few meters, whereas others have held that the platforms are being cut under present conditions simultaneously with the cutting of the normal marine bench below low tide. This latter view is supported by observations along the coast of Punta Concepcion. The notches at the inner edges of the platforms show considerable chipping after each storm; hence the platforms are being cut at the present time and so do not indicate a recent emergence of the shore line.

MINERALIZATION.

The striking feature of the manganese deposits on Punta Concepcion is the abundance of the pyrolusite veinlets. In low grade ore tiny veinlets up to an inch (two or three centimeters) wide are spaced at intervals of 10 or 15 feet (3 or 4 meters). In average ore the veinlets are of about the same width but with closer spacing, and in high grade ore the veinlets may constitute almost 50 percent of a face. Disseminated ore is not common. In typical ore the narrow, sharp-walled veinlets of pyrolusite break easily from the basalt and, except for some loss in fines, make almost ideal ore for hand sorting.

The distribution of the products of mineralization is shown in Figure 4. Considerably more than the pyrolusite of the mine area is included under the heading of mineralization, as the pyrolusite veins are only part of a widespread process of mineralization comprising a variety of minerals. The products of

[5] Wentworth, C. K., Marine bench-forming processes: water-level weathering: Jour. Geomorph., vol. 1, 1938. Bartram, J. A., Shore platforms (discussion): Jour. Geomorph., vol. 1, 1938. Johnson, Douglas, Shore platforms (discussion): Jour. Geomorph., vol. 1, 1938. Wentworth, C. K., Marine bench-forming processes: solution benching: Jour. Geomorph., vol. 2, 1939. Jutson, J. T., Shore platforms near Sydney, New South Wales: Jour. Geomorph., vol. 2, 1939. Wentworth, C. K., Shore platforms near Sydney: a discussion: Jour. Geomorph., vol. 3, 1940. Edwards, A. B., Storm-wave platforms: Jour. Geomorph., vol. 4, 1941. Stearns, H. T. Shore benches on north Pacific islands: Geol. Soc. America Bull., vol. 52, 1941. Stearns, H. T., Eustatic shore lines in the Pacific: Geol. Soc. America Bull. vol. 56, 1945.

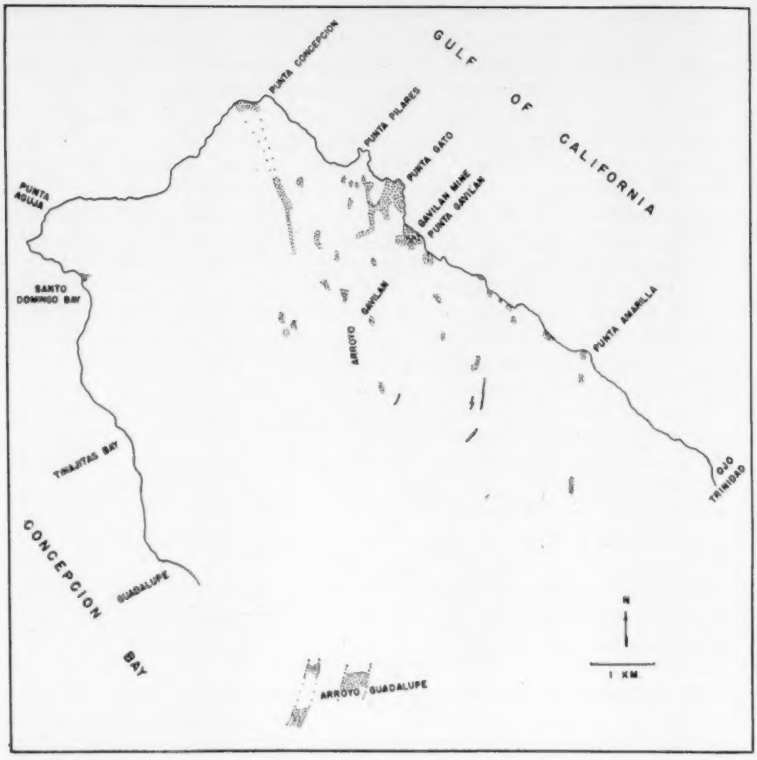


FIG. 4. Distribution of the products of mineralization (pyrolusite and other minerals) on Punta Concepcion.

mineralization spread over most of the northern half of the peninsula and extend to, or recur in, the southern part. The principal locus of mineralization is that of the mine area, on Punta Gavilan and Punta Gato. There the mineralization is nearly continuous throughout the basalts of the mine series, except for parts of the lowest basalt. To the west and southwest from Punta Gato are many small irregular areas of mineralization, some of which show copper rather than manganese. Another important locus of mineralization occurs about 2 kilometers inland from Punta Gato, extending in a direction a little west of north. Here the manganese mineralization extends for about a kilometer; then there is a gap possibly due to poor exposures; and on the same line on the coast at a distance of another kilometer is a wide zone of calcite veins. Also about a kilometer to the south there was found an indistinct zone of manganese and calcite veins. A

third somewhat less definite zone of mineralization occurs along the coast between the Gavilan mine and Punta Amarilla and in the high peaks of conglomerate to the southeast. Several strong, well defined veins have been mapped in this area, but the strongest veins are mainly white calcite with only a little accompanying pyrolusite. There are some spots of copper mineralization in this zone. The mineralization in and near Arroyo Guadalupe may be a distinct zone of mineralization or possibly an extension of one of the other zones. These veins carry much calcite, and some carry only calcite. A very small spot of very weak manganese mineralization at Santo Domingo Bay is, except for the Guadalupe zone, the only mineralization which has been found on the west side of the peninsula.

The age of the manganese mineralization can be fixed fairly definitely in relation to the geologic history. The veins cut all the rocks except the shell bed and some recent sedimentary rocks near Santo Domingo Bay, and detrital manganese grains accumulated in that shell bed. The manganese veins formed, therefore, in the interval between the accumulation of the first conglomerates of the sedimentary series and the shell bed.

Two types of structural control of manganese mineralization are noted; in places the ore is most abundant along fault zones regardless of the type of rock, and in other places certain beds carry more abundant ore than do the surrounding rocks. The control by faults is seen clearly in the mine area, where the best ore occurs in and along fault zones. The faults at Punta Gavilan strike a little west of north, dip to the west, and show normal displacement. On Punta Gato, the faults which control mineralization also strike west of north but are not uniform in dip or displacement. Several other areas suggest the localization of mineralization along faults. On the other hand, the control by faults is rather selective, in that, taking the district as a whole, most faults show no evidence of mineralization.

In detail the mineralization of the mine area is seen to be guided by a fracture pattern which for the most part also strikes a little west of north, although the pattern is very complex, and there are many exceptions. Where the basalt is thoroughly shattered, as in so much of the mine area, veinlets trend in all directions, but there is almost everywhere a noticeable tendency to trend a little west of north, as the faults do.

The stratigraphic control of mineralization is most noticeable at Punta Gavilan, where an upper basalt is everywhere well mineralized but a lower basalt carries ore only near the main faults. On Punta Gato the same control operates; the same lower basalt is relatively weak in mineralization while the upper basalt and several higher ones are good. Ore is found well down into the lower basalt, however, in the area to the west and southwest of Punta Gato. Although nearly all the good ore is in basalts, there is some fairly good ore in intrusive rocks, and there are many veins, though mostly low in manganese, in the lower conglomerate of the sedimentary series.

The manganese phase of the mineralization is the only one commercially important. In most of the tiny veins of the mine area, pyrolusite or a manganese oxide mineral very near pyrolusite in chemical and physical properties is the

only mineral. In some of the veinlets, however, there are a few gangue minerals, in the following paragenesis (from youngest to oldest):

aragonite
calcite
dolomite
limonite
quartz
pyrolusite
vanadinite.

Vanadinite has been found in place in only one specimen, in stubby lemon-yellow crystals which were coated by pyrolusite. Quartz has been found in a very few specimens and is later than pyrolusite but not related to the other gangue minerals. Limonite in tiny yellowish red fibrous bands coats pyrolusite in a number of specimens and is followed by the carbonates. Dolomite and calcite have been identified in a few specimens but not in the same specimen; their relative ages are not known, but they are always later than pyrolusite. Aragonite is the most abundant gangue mineral, forming narrow medial bands of fibrous texture in many veins. It is the latest mineral in all the specimens seen.

Through the kindness of M. Fleischer of the U. S. Geological Survey, some specimens thought to show crystal faces of pyrolusite were determined by X-ray study. The specimens submitted had small stubby crystals of a manganese oxide mineral perched on massive black manganese oxide. The crystals were determined to be ramsdellite, a dimorph of pyrolusite, and the massive material was hollandite, probably with amorphous material.[6] Qualitative tests of the massive material indicated the presence of much barium and some cobalt and vanadium. Hollandite is believed to have the formula BaR_8O_{16}, in which R is Mn^{IV} chiefly, also Fe^{III}, Mn^{II}, and Co.[7] The results of these determinations show that the mineralogy of these manganese ores is more complex than is suggested by field study. The predominant manganese oxide may not be pyrolusite but one or more of the other oxides. Analyses of shipments and special samples show, however, that the bulk of the ore is either pyrolusite or its dimorph ramsdellite, because the MnO_2 : Mn ratio is too high and impurities are too low for any great amount of a mineral departing appreciably from the formula MnO_2. There is enough BaO in some determinations, however, to account for an admixture of a few percent of hollandite with the other oxides. The source of the appreciable lead in concentrates and hand sorted ores has not been identified; not enough vanadinite has been found to account for it. Possibly there is an appreciable amount of one of the lead bearing manganese oxide minerals whose presence has not been established.

A few additional minerals have been noted in areas away from the mine area. Barite is found in a few veins, and in some of these are secondary copper carbonates. The primary copper minerals have not been found. Some strong

[6] Fleischer, M., Personal communication.

[7] Fleischer, M., and Richmond, W. E., The manganese oxide minerals: a preliminary report: Econ. Geol., vol. 38, p. 274, 1943.

veins in the high peaks of conglomerate southeast of the mine are white calcite with a small amount of pyrolusite. The veins of the Guadalupe claim, on the south side of Arroyo Guadalupe, carry black manganiferous calcite in coarse cleavable crystals.

In the vicinity of the mine area at Punta Gavilan the basalts have undergone a widespread and general chloritization. The rocks are definitely more green in this area, and the microscope shows that the augite has been fairly generally chloritized. Areas that show less chlorite are those in which there is less ore; this is particularly true of the relatively barren lower basalt. Farther from the mine area, some ore is found in unchloritized basalts and some chloritic areas occur without manganese; but on the whole the relationship between chloritization and manganese mineralization is close.

The veins that make up the manganese deposits of Punta Concepcion are believed to be primary veins of hydrothermal origin. The minerals of the veins are mainly crystalline pyrolusite, ramsdellite, hollandite, and aragonite. Countless veins cut the basalts in all directions, and very large amounts of material have been introduced into the rocks. In the main deposits there are no other manganese-bearing minerals that could have been the source of the manganese. Only in the small deposits in Arroyo Guadalupe is there any manganiferous calcite. This occurs at depths of one or two meters from the surface and is capped by a deposit of soft, sooty manganese oxide wholly unlike the hard, sharp walled veins of the main deposits.

A hydrothermal origin has been ascribed by Wilson and Veytia [8] to the Lucifer and surrounding deposits near Santa Rosalia, about 30 kilometers north of Punta Concepcion, and by Park [9] to manganese deposits in Cuba.

CALIFORNIA INSTITUTE OF TECHNOLOGY,
PASADENA, CALIFORNIA,
August 5, 1950.

[8] Wilson, I. F., and Veytia, Mario, Geology and manganese deposits of the Lucifer district northwest of Santa Rosalia, Baja California, Mexico: U. S. Geol. Survey Bull. 960-F, pp. 177–233, 1949.

[9] Park, C. F., Jr., Manganese deposits of Cuba: U. S. Geol. Survey Bull. 935-B, pp. 75–97, 1942.

STRUCTURAL CONTROL OF OREBODIES AS ILLUSTRATED BY THE USE OF VEIN CONTOURS AT THE O'BRIEN GOLD MINE, CADILLAC, QUEBEC.

JOSEPH W. MILLS.

ABSTRACT.

This paper is an account of the method and results of constructing vein contours for the purpose of visualizing vein deflections in space and correlating them with ore shoots. Such a correlation is shown to exist for the gold-bearing veins of the O'Brien Mine indicating that the position and attitude of sites favorable for late gold deposition were determined principally by vein attitude. Other structural features, such as vein intersections and folds, are shown to have had a strong localizing influence on the ore. The recognition, plotting and projection of these controls on vein contour sections are helpful in determining sites likely to be ore-bearing and so worthy of mine exploration.

INTRODUCTION.

THE purpose of this study was to determine and record the presence of any structural control for the gold ore and to apply such knowledge gained to a systematic and economical method of developing ore in sight and finding new ore.

Since the veins have somewhat similar strikes and almost vertical dips an examination of orthodox mine geology plans and sections failed to indicate any obvious ore control. Veins of slightly different strike, dip, width and length all contain ore shoots. Ore has been found in veins in all the host rocks and along formation contacts with no particular horizon appearing to be a favorite for ore.

It was decided then to construct longitudinal contour sections to show all the features recorded in the course of geological mapping. Any correlation between ore and subtle changes in strike, dip or width of the vein, type of alteration, host rock or mineralogy, et cetera, would be evident, should it exist.

The O'Brien Mine is in Cadillac Township, Abitibi County, Northwestern Quebec, about 50 miles east of the Quebec-Ontario provincial boundary, on the Montreal-Val d'Or-Noranda Highway. The mine workings are within a few tens to hundreds of feet of the major fault known as the Cadillac Break or Shear Zone, which has been traced in an east-west direction for over 80 miles in Northwestern Quebec alone.

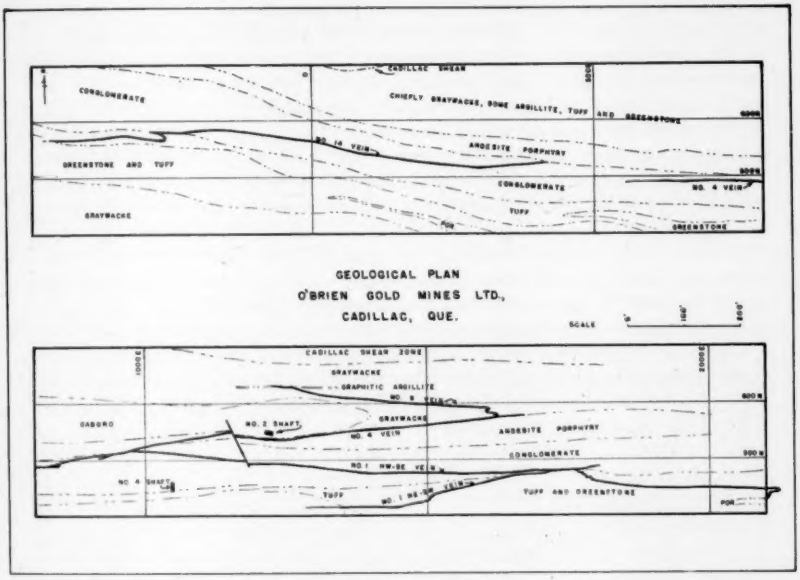
The mine is developed from three vertical shafts: No. 2 extending from the surface to 2,000 feet; No. 3 from surface to 1,500 feet; and No. 4 from 2,000 to 3,500 feet. The deepest development by drifting and crosscutting is on the 3,000 level.

Production to the end of September 1949 amounted to 427,031 fine ounces of gold from 851,697 tons of ore having an average grade of 0.501 ounce a ton.

Of this total only 5.6 percent of the tonnage and 3.8 percent of the ounces came from No. 3 shaft area and no mining has been done there since 1943. For these two reasons the present study was confined to the No. 2–4 shaft area.

GENERAL GEOLOGY.

For a detailed discussion of the regional geology and full descriptions of rock types the reader is referred to government reports (1–6) [1] as well as a paper by Robert A. Brown (7). It shall have to suffice here to say that the mine is in a steeply dipping series of Precambrian igneous and sedimentary rocks which strike approximately east-west. A section from north to south



FIGS. 1A AND 1B.

in the vicinity of the working shows the following formations: Cadillac Shear (talc-chlorite schist), graywacke and argillite with some gabbroic bodies, andesite porphyry, conglomerate, tuff and greenstone, andesite porphyry, tuff and greenstone, and graywacke farthest south. The reader is referred to Figures 1A and 1B for a picture of the distribution of strata in the vicinity of the mine workings. The formations are isoclinally folded and the presence of axial plane cleavage or schistosity and highly deformed conglomerate pebbles illustrate the rock metamorphism. The rocks, although retaining many of

[1] Numbers in parentheses refer to Bibliography at end of paper.

their original characteristics, have been sufficiently metamorphosed to make it difficult to distinguish between bedding planes and planes of axial cleavage for the two are almost parallel. Reliable top determinations have never been made.

ORE-BEARING VEINS.

Production from the No. 2–4 shaft area has come from five veins, No. 1 NW-SE, No. 1 NE-SW, No. 4, No. 9 and No. 14.

The veins are tabular bodies of quartz mineralized with arsenopyrite and gold with minor amounts of pyrite, pyrrhotite, scheelite, calcite, tourmaline and albite. The quartz is for the most part well fractured and bluish gray in color although milky white quartz is not uncommon and black quartz is seen occasionally. The vein quartz commonly shows good "book" and "leaf" structure, which, taken with the well developed longitudinal fractures, imparts a lamellar characteristic to the vein filling. The "books" and "leaves" exhibit most of the features described by McKinstry (8) and are taken to indicate that replacement played an active part in vein formation.

Arsenopyrite occurs as small disseminated rhombohedral grains and acicular crystals in the quartz, chiefly within the "leaves" or included wall rock lamellae and very abundantly in the altered wall rock. Mill production figures from 1940 to 1949 indicate that the average content of arsenopyrite in the ore is 1.3 percent.

Native gold occurs in the quartz in small fractures approximately parallel to the vein walls and as "smears" on sericite shear surfaces in the quartz and at the vein-wall contacts. In a few places the gold-filled fractures in the quartz are numerous both across the vein and parallel to its walls and attain widths of a half inch, resulting in a spectacularly rich grade of ore. Gold is also associated with arsenopyrite where it occurs as a filling of minute crystal fractures.

The veins may be grouped into two categories according to their attitude with respect to their host rocks:

Group A.

This group includes veins No. 4, No. 14 and No. 1 NE-SW. They strike slightly more northeasterly and dip more flatly south than the enclosing rocks. Where "folds" are present in the vein they are of the S type. Branching veins are of the group B type. Left-hand strike changes appear to be more favorable locations for ore.

Group B.

In this group are included veins No. 9 and No. 1 NW-SE. They strike more northwesterly and have a vertical to steeply north dip. Where "folds" are present they are of the Z type. Branching veins are of the Group A type. Right-hand strike changes seem to be more favorable for ore.

Brown (7) recognized only three major veins in the No. 2–4 shaft area, namely, No. 1, No. 4 and No. 9. Development in the past few years has demonstrated that the No. 1 Vein is actually two veins crossing each other in such a way as to have the form of a flattened X. There is no necessity to suppose, as Brown did, that the No. 9 Vein and "later part" of No. 1 Vein, that is the

NW-SE Vein, were formed at a later time than No. 4 Vein. The lack of displacement, perfect blending of quartz and similar mineralogy at the intersection of the veins of the two groups point rather to formation at the same time as a set of complementary fractures in response to the same stress. The alteration of the wall rock along No. 9 Vein differs chiefly in amount from the other veins and can be explained by the different character of the unaltered rock.

The writer agrees with Brown (7) as to the origin of the vein folds. These have been localized chiefly at formation contacts and represent quartz filling and replacement of a series of complementary fractures of the Group A and Group B types.

Post-ore strike-slip faults are common throughout the mine. Displacements are usually measured in inches though they have been found to be as great as 15 feet. These late faults strike either northeasterly or northwesterly, the former having a left-hand throw and the latter a right-hand throw. Fault dips are from vertical to 45 degrees in either direction.

Since many of the gold-filled vein fractures are parallel to the late faults it has been suggested by Gunning (9) that "the parallel fractures were caused by the same stresses as the faults." He offers an explanation for the high-grade shoots on the assumption that they have been localized by an intensification of vein fracturing adjacent to the cross-cutting faults. To quote the above reference once more, Gunning says, "fracturing of veins should be most intense near major or numerous diagonal faults."

Geologic mapping during the eight years since the writing of Gunning's paper has demonstrated that his hypothesis for the localization of ore shoots is incorrect. It is believed that the similarity in strike and dip of some of the gold-filled fractures and the diagonal faults is fortuitous and that there really was a considerable time lapse between the gold deposition and the faulting. A few diagnostic features which support this more modern view may be mentioned. Vein fractures have a much greater variety of strike and dip than the faults, the most persistent fractures paralleling the vein walls. Vein fractures, though very numerous and plain to see, never pass beyond the quartz. Faults are invariably barren and have a characteristic wall-rock alteration entirely different from vein wall-rock alteration. Gold-bearing portions of the veins have been displaced along reverse faults which strike almost parallel to the veins and these reverse faults have in turn been displaced by the diagonal faults. The most convincing argument against ore shoot localization by diagonal faults results from a study of the longitudinal sections of the veins (Figs. 2–6). The traces of the intersections of the major faults with the ore-bearing veins are shown on the sections generally traversing great areas of waste. Ore shoots pitch parallel to, steeper or flatter than, the fault traces, commonly cross them, and generally occupy a position well to their side.

VEIN CONTOUR SECTIONS.

Geological plans on scales of 1 inch to 20 feet and 1 inch to 100 feet, and sections on a scale 1 inch to 40 feet are kept up to date illustrating all the detailed geological features exposed during the course of mining. In order to

study geological features in relation to the ore sections of the individual veins in three dimensions it was found convenient to use contour sections. The idea of studying a vein by the contour method is not new. Conolly (10), in an excellent paper, explains the construction and use of both contour plans and sections. Newhouse (11) has demonstrated their applicability in the interpretation of vein attitudes in space and their relation to ore shoots. Derry (12) mentions their application and deplores their limited usage.

On a vein contour section, points along the vein equidistant from some arbitrarily chosen plane, usually the plane which approximates the average strike and dip of the vein, are joined in much the same way that points of equal elevation are contoured with respect to their distance from a horizontal plane in the construction of a topographic map. The resulting contours represent the loci of points along the vein which are equidistant from the arbitrarily chosen plane and so illustrate in a graphical way the deviations in the attitude of the vein from the chosen plane. The use of contour sections is not limited to a study of vein attitudes but contours may be drawn for vein widths, assays, assay-widths, or other pertinent statistical data. Such features as faults, folds, types of alteration, type of wall rock, branch veins et cetera may also be drawn on the contour sections and their relations to the contours studied.

Contour sections of the O'Brien veins were prepared using as reference plane (a) an east-west vertical plane, (b) an east-west plane inclined parallel to the average dip of the vein, (c) a vertical plane parallel to the average strike of the vein, and (d) an inclined plane approximately parallel to the average dip and strike of the vein. Due to the fact that the average strike and dip of the veins at the mine are within 10° of east-west and vertical it was found that contour sections of type (a) above showed all the features illustrated by the other three types of contour sections. Another factor which favors the use of a vertical east-west reference plane is that the mine coordinates are north-south and east-west so that the contours are actually vein latitude contours. It can be readily understood that this simplifies plotting and makes for speed and facility in interpretation when reference is made to the sections for a clue to some current mining problem.

The procedure usually followed in the preparation of a vein contour section will now be outlined. By reference to the geological plans a vertical east-west section is prepared showing all the drifts, crosscuts, backstopes, stopes, raises, and any other mine workings in which the vein to be studied is exposed. All diamond drill holes which intersect the vein or traverse the region where the vein is expected are plotted at the elevation and departure of the intersection or expected intersection. The vein latitudes are then plotted on the section of the mine workings at some convenient spacing along the departure direction. This spacing is determined by the scale of the section, the contour interval chosen and the complexity of the vein structure. On a vertical section with a 100-foot scale and a contour interval of 5 feet, for example, a plotting of vein latitudes every twenty feet along the departure direction will usually suffice, with more numerous plotting where abrupt changes in vein attitude are present. Vein latitudes of diamond drill hole intersections are plotted alongside the drill holes shown on the section. Some convenient contour interval is

chosen, say 5 feet, and the points contoured, extrapolating where it is necessary as in the case of most of the diamond drill holes. Crest lines and valley lines may also be drawn as suggested by Conolly (10). These lines simplify the interpretation of the general picture but do not reflect the changes in vein attitude as well as the contours. Crest and valley lines illustrate the loci of changes in strike, for example, but do not demonstrate the more subtle rate of change in strike as expressed by a varying spacing of contours along the strike direction. A study of the vein attitude in space may now be made in the manner described by Newhouse (11). Any degree of correlation between vein attitude and vein grade will be apparent, should it exist.

Group A.

Vein No. 4.—Vein No. 4 has been explored in an east-west direction for a length of slightly over 1,500 feet and vertically to a depth of 3,000 feet. In its lateral extremities it expresses itself as a stringer less than an inch in width with very slight attendant alteration and mineralization. Development of the vein on the 3,000-level is limited in extent but such work as has been done shows it to be similar in all respects, except grade, to the vein throughout the mine. The average strike of the vein is N 86° E and average dip is 86° south. At its western extremity the host rock is conglomerate (Fig. 1A). To the east the vein gradually cuts across the following formations, conglomerate, porphyry, mixed greenstones and graywacke, in that order, apparently diminishing to insignificant proportions in the graywacke. In places the vein attains a width of 5 or 6 feet but the average width of the quartz is probably of the order of a foot to a foot and a half. Branching veins of the Group B type are fairly common, most of which are small and of limited extent. Branching is best developed where the vein is at a formation contact. The best example of such a branch or complementary vein is No. 9 Vein which joins No. 4 at the porphyry-graywacke contact and has been a major producer. Since No. 4 strikes slightly more northeasterly and dips more southerly than the enclosing rocks the intersection of the vein with the strata pitches steeply to the east. Intersections with veins of the Group B type also pitch at a steep angle to the east. Porphyry, conglomerate, and their contact are hosts for high-grade, low-grade and waste portions of the vein so that no one formation can be said to be more favorable.

Contour Section No. 4 Vein.—Construction of this section (Fig. 2) was carried out as described above. In order to eliminate confusion due to reproduction of the section on a small scale no stopes are shown and a contour interval of 10 feet is used rather than the original 5 feet. Ore types have been limited to two, according to whether the product of width in feet × ounces of gold per ton is (1) mine average plus or minus 20 percent or (2) considerably better than mine average and high grade. There are three major ore-bearing areas in No. 4 Vein, and two minor ones. From the 750-level to surface east of departure 1,500 E ore has been mined continuously. Throughout the major part of this shoot the latitude contours are closely spaced and are steep. They indicate the vein to have a strike considerably northeast of the average and a

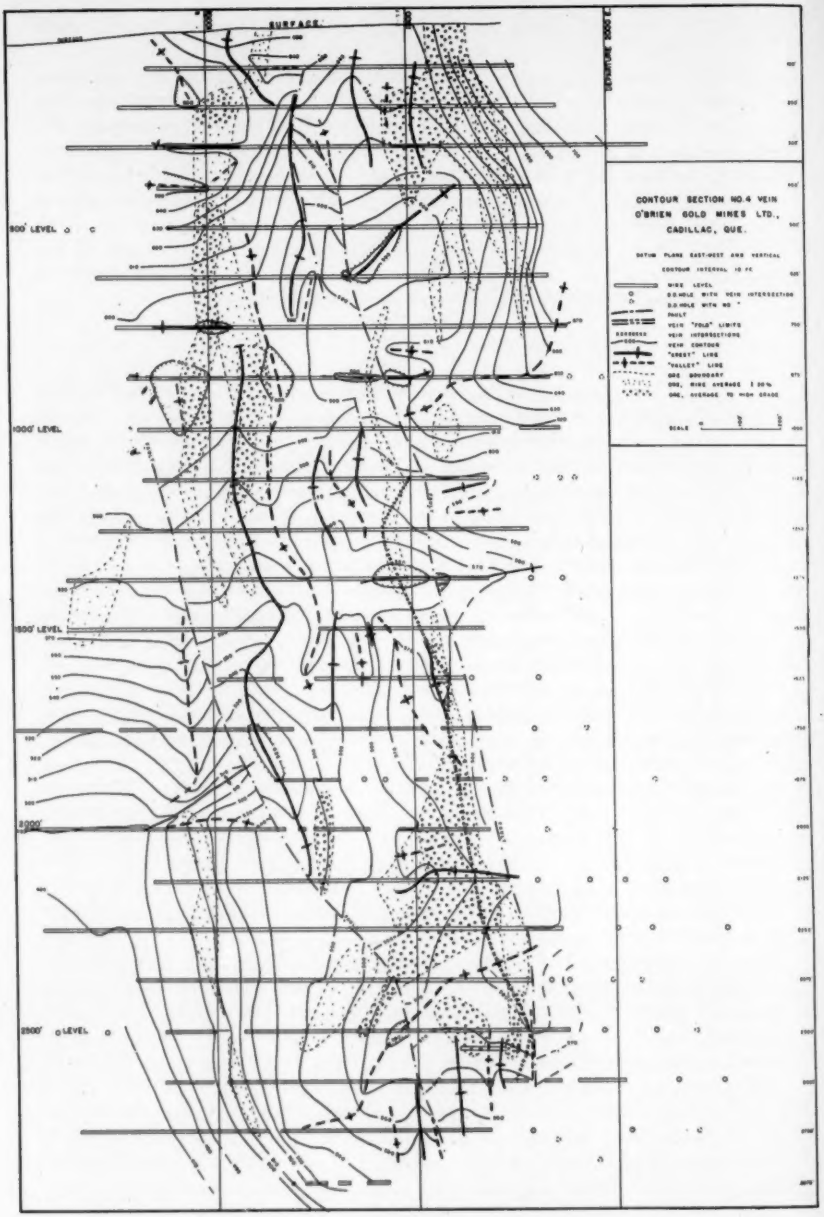

SURFACE
800' LEVEL
1000' LEVEL
1800' LEVEL
2100' LEVEL
CONTOUR SECTION NO. 4 VEIN
O'BRIEN GOLD MINES LTD.,
CADILLAC, QUE.

FIG. 2.

steep to vertical and reverse dip. On the 200- and 300-levels ore of good grade extends for 50 feet west of the "crest" line at departure 1,500 E into an area of right-hand vein strike. Below the shoot the contours flatten to almost a horizontal direction, indicating the vein to have changed to an east-west strike and a relatively flat south dip and the vein ceases to be ore bearing. Development has not been extended far beyond the ore limits to the east chiefly because the vein passes into graywacke and becomes small. A bending of the steep contours toward a horizontal direction at the east end of the 750- and 875-levels suggests that there is a valley east of the ore-bearing area. Left-hand strike changes and steep dips seem then to coincide with the position of this ore shoot.

Ore has been mined continuously from the 2,500-sublevel to the 1,875-level to the east of departure 1,400 E. Contours stand steeply here and flatten abruptly below the 2,500 level. The vein has a northeasterly strike. Diamond drilling beyond the mining limits to the east suggests that there is a "valley" immediately east of the mining limits and that east of this again the vein strikes south of east. The shoot appears to be limited to the east and below by right-hand strike changes and flat south dips in the same manner as the shoot east of departure 1,500 discussed above. The reason for the tapering of the ore shoot above the 2,000-level is not clear. From the 1,875- to the 1,500-levels the ore is immediately east of a "crest" line close to the junction with No. 9 Vein. Between departures 1,300 to 1,500 E from the 2,000- to 1,500-levels the vein has a steep dip and a strike which is left hand relative to the extension to the west but there is not a great deal of ore here. This may be partially accounted for by the fact that No. 9 Vein, a branch of No. 4, lies to the north of No. 4 in this area and is of very good grade. The position of the intersection of No. 4 and No. 9 Vein is shown in Figure 2 as a line of xxxx's from the 1,125- to 2,625-levels. The bulk of the ore in the shoot coincides in position with a portion of No. 4 Vein which has a left-hand strike and a steep to reverse dip. The intersection of No. 9 Vein with No. 4 appears to have had some influence on the position of the ore since its trace on the vertical longitudinal section coincides with the longer shoot dimension. As illustrated in Figure 6 the best ore in No. 9 Vein lies between the 2,125- and 1,375-levels at and west from its junction with No. 4. This is just the area where the amount of ore in No. 4 Vein is small in spite of its favorable attitude. It would appear that the steep south dips of No. 4 above the 2,125-level were not as favorable as the vertical and reverse dips of No. 4 below the 2,125-level and No. 9 above the 2,125-level.

From the 2,000- to the 2,750-levels a small ore shoot of low to moderate grade has been outlined by drifting in the vicinity of the 1,000 E departure. The position of the ore shoot coincides with a portion of the vein that has a steep dip and a strike that is left hand relative to the bordering waste areas as is indicated by the steep contours and their crowding together in the vicinity of the ore shoot. Its upper and lower limits are marked by a flattening of the contours.

A discussion of the ore-bearing area of No. 4 Vein which lies between the surface and the 1,500-level to the west of departure 1,200 E has been left to the

last for two reasons; first, the portion of the shoot lying between the 500- and 1125-levels is, by far, the richest in the mine, and second, because at first glance the contours appear to be of the type that are unfavorable in the other three shoots discussed above. From the 200- to the 750-levels the ore shoot is of moderate to high grade and quite regular in form. The contours here are rather flat which might seem to present an anomalous condition from those found elsewhere in the No. 4 Vein ore shoots. The contours to the east of the shoot limits are steep and form the west side of a pronounced "crest." The vein within the shoot has a strike that is east-west and left hand relative to that portion of the vein east of the shoot, which strikes strongly to the south of east. Below the 750-level the shoot splits into two spectacularly rich shoots separated by a horse of waste. Below the 1,125-level, the grade of the two shoots drops off rather abruptly. Of the two branches of the shoot below the 750-level the east one occurs between a "crest" line on the west and a "valley" line to the east and so conforms very well to a portion of the vein that has a pronounced left-hand strike relative to the strike of the vein beyond the limits of the ore. It is not known why the east shoot did not continue through the 1,250- and 1,375-levels between the "crest" and "valley" lines. For three levels below the 1,375-level the vein between these lines is contained within a shaft pillar. Coarse gold is known to be present but the size and shape of the shoot are unknown. A small shoot of moderate grade is present between the 1,875- and 2,125-levels just to the east of the same "crest" line. The strike of the vein within the shoot is left hand with respect to the strike to the east and particularly to the west of the shoot. The west branch below the 750-level, of the important rich shoot, follows a part of the vein with a right-hand strike. The author can find no satisfactory explanation of this anomaly, which is particularly lamentable in view of the uncommonly high grade of the ore. At the time mining was proceeding on these upper levels geological mapping was done on a scale of 40 feet as contrasted with a scale of 20 feet for the lower levels. This difference in mapping detail would not be responsible for any appreciable change in contour attitude but it is conceivable that the mapping may have overlooked some feature of the geology that would give a clue to the anomalous ore behavior. A recent sill-recovery job in this west shoot branch afforded the author the opportunity of examining a breast 17 feet high where the vein was a few inches wide and spectacularly rich. The quartz is highly fractured and the fractures are filled with gold. The vein is in an altered and highly schistose porphyry less than six inches from the porphyry-graywacke contact. The graywacke at this place is represented by a 10-inch bed of highly graphic argillite bordered on the north by normal graywacke. The interesting, and possibly significant, point is that the presence of this graphitic horizon had never been indicated on mine or geology plans or sections. The presence of the graphitic horizon along the porphyry-graywacke contact undoubtedly served to localize movement along the contact as is evident from the uniquely highly schistose nature of the vein walls. The presence of an unusually large amount of gold in the highly fractured vein where rock failure has been localized by the graphitic horizon may not be fortuitous. It is interesting to note at this point that there is a considerable enrichment of No. 9 Vein where it terminates to the west against a similar graphitic horizon.

Another shoot of short lateral extent occurs between the 750- and 1,375-levels approximately at departure 1,450 E. It is a continuation, above the strong horizontal "crest" line, of the major ore shoot below the 1,500-level. The intersection with No. 9 Vein and the presence of a steep "crest" line to the west, indicating the shoot to be within a portion of the vein with a left-hand strike, have probably been responsible for the position of the ore.

A low grade shoot at the west end of the 1,250-, 1,375- and 1,500- levels does not seem to have been localized by any particular strike change but dips are slightly steeper than average for the area.

No. 1 NE-SW Vein.—No. 1 Vein has been developed in an east-west direction for a length of 2,000 feet above the 625-level and vertically to a depth of 3,000 feet. Average strike of the vein above the 1,000-level is about 2 degrees south of east and the dip is 84° south. Below the 1,000-level the strike is more nearly 10° south of east and the dip 87° south. Average vein width is somewhat less than a foot.

All of the vein exposed at surface is within the conglomerate formation. Down the dip and to the west it passes into tuff. From the 875-level to the 2,500-level that part of the vein west of the junction with No. 1 NW-SE is in tuff and the part east of the junction in conglomerate. Diamond drilling to the east of the vein junction indicates that the vein becomes very small and probably pinches out. Below the 2,500-level the junction of the two No. 1 Veins flattens and passes into the tuff. Ore then continues from the junction eastward as far as the intersection of the No. 1 NE-SW Vein with the tuff-conglomerate contact where the vein makes a series of S-shaped "folds," becomes quite rich and then rapidly pinches out in the conglomerate.

Diamond drilling to the west of the mine workings below the 500-level suggests that the vein pinches out so that its average length here is about 900 feet.

Contour Section No. 1 NE-SW Vein.—Between the surface and the 500-level (see Fig. 3) there are three main ore shoots. The westernmost shoot, between departures 200 and 300 E, lies just to the east of a "crest" line, that is, within a portion of the vein which has a left-hand strike relative to its extension to the west. The ore on the 300-level is much higher grade than that on the 500-level, which may be explained by the presence of a "valley" line only one hundred feet to the east of the "crest" line indicating a more sinuous trend for the vein on the 300-level than on the 500-level where the next "valley" line lies 300 feet to the east. The next important shoot extends from surface to the 300-level between departures 500 E and 850 E. The lower westernmost part of the shoot lies immediately west of a "valley" line. The ore does not extend downwards as far as the 500-level, a feature that may have been influenced by the presence of a reversal in dip between the 300- and 500-levels. The upper half of the shoot has a right-hand strike relative to the area to the east. It is interesting that, although drift channel assays indicated the vein to be of ore grade between the 100- and 200-levels in this "unfavorable" area, when backs were taken down as a preliminary step in mining the muck was not of ore grade and no stoping was done between these two levels. The east part of the shoot lies between a "crest" line and a "valley" line, that is, within a portion of the vein with a left-hand strike. The bottoming of the shoot below the 300-level coincides with a fading out of these two structural lines and a pronounced

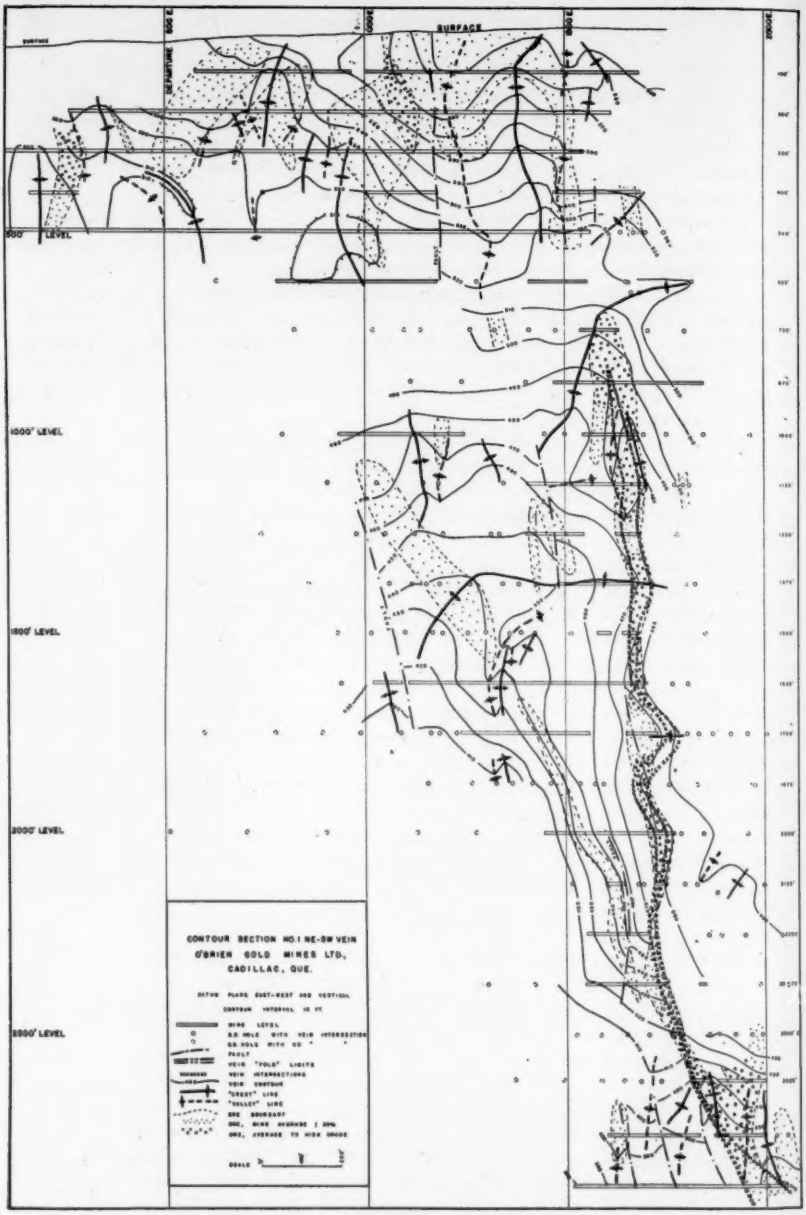

SURFACE
500' LEVEL
1000' LEVEL
1500' LEVEL
2000' LEVEL
2500' LEVEL
CONTOUR SECTION NO. I NE-SW VEIN
O'BRIEN GOLD MINES LTD.,
CADILLAC, QUE.

FIG. 3.

steepening in dip of the vein. The next, and largest ore shoot above the 625-level, occurs between departure 950 and 1,550 E with a form similar to an arch or inverted U on longitudinal section. It is separated from the ore shoot just discussed by a short length of waste which has a slightly more right-hand strike and flatter dip than the vein in the bordering ore shoots.

The west half of the ore shoot is bounded on the west by a "crest" line, with the better grade ore on the upper levels where strike changes are more abrupt and dips are steeper. Above the 300-level, low-grade ore extends beyond a "valley" line to the east into an area with a right-hand vein strike. The bending of the contours is not abrupt here so that the positioning of the "valley" line is more arbitrary than usual. The more gradual strike change appears to have permitted a less abrupt termination of ore values. About departure 1,500 E the east leg of the shoot has been localized chiefly by an abrupt change in strike, though almost as much ore lies to the east of the "valley" line as to the west.

Below the 300-level between departures 1,100 and 1,500 E the bending of the contours becomes increasingly less abrupt and flatter until below the 625-level they are almost horizontal. In this area, which extends as far as the 1,000-level, the vein is essentially a south-dipping east-west plane containing no ore.

Knowledge of ore shoots on the No. 1 NE-SW Vein is not nearly as complete below the 625-level as it is for the No. 1 NW-SE Vein. Diamond drilling of the former vein has been frequent and has served to outline areas worth investigation but the information is not yet sufficiently reliable to outline ore shoots positively.

One persistent ore shoot of very good grade in No. 1 NE-SW Vein extends from the 750-level to beyond the 2,875-level between departures 1,550 and 2,000 E. No. 1 NW-SE Vein and No. 1 NE-SW Vein come together to form one vein between the steep rows of X's shown on Figure 3. The persistent ore shoot referred to above falls at or adjacent to this junction of the two veins. The enrichment of one or both veins at their junction is a feature already emphasized in the discussion of No. 4 Vein.

While discussing the junction of No. 1 NE-SW and NW-SE Veins it is appropriate to consider at this time the position of the junction with respect to rock types. From the 1,125- to 2,250-levels, where the contours indicate the vein to have a steep to vertical dip, the junction of the two veins is at the tuff-conglomerate contact. Below the 2,250-level the contours indicate that the vein has flattened in dip. Since this is not paralleled by an abrupt flattening in dip of the tuff-conglomerate contact, the vein and vein junction pass downward into the tuff to the south of the conglomerate. Above the 1,125-level a similar flattening in dip of the vein, shown on Figure 3 by the horizontal contours, causes the vein and vein junction to pass upwards into the conglomerate to the north of the tuff. The junction has been shown as fading out about the 750-level. The reason for this is that the No. 1 NW-SE Vein fails to express itself shortly after passing upwards into the conglomerate.

From the 1,125-level at departure 1,000 E to the 2,375-level at departure 1,660 E diamond drilling and drifting have outlined a possible low-grade ore

shoot. That portion of the shoot above the 1,625-level has been found by diamond drilling only, and shows no preference for a particular strike or dip. Below the 1,625-level the shoot has a very short east-west length and is confined to an area of steep, closely-spaced contours, which indicate the vein strike to be left hand.

Ore of very good grade extends east of the No. 1 NW-SE and No. 1 NE-SW junction below the 2,500 level for as much as 150 feet. It lies within a portion of the vein that has a pronounced left-hand strike as is indicated by the presence of a "crest" line to the west and a "valley" line to the east of the shoot.

West of the vein junction below the 2,625-level there are three "valley" lines and one "crest" line due in part to the fact that faulting has complicated the vein pattern. No ore has been found except for the presence of some spotty visible gold at the west end of the 2,750-level drift.

Six out of eight diamond drill holes on the 2,500- and 2,625-levels west of departure 1,700 E are within a "favorable" area; still they failed to cut any mineralization so that the vein must be very small or absent. Since ore, as specified in this paper, is determined as a product of width x grade, the absence of ore in a "favorable" area does not necessarily invalidate the theory. It is possible for a vein to have an attitude favorable for ore deposition and to contain gold and still be too narrow to mine at a profit.

All of the better grade ore and most of the low-grade ore in No. 1 NE-SW Vein appears to have been localized by (1) junction with No. 1 NW-SE Vein at and near tuff-conglomerate contact and (2) left-hand strike changes as indicated by (a) ore lying to the east of "crest" lines and west of "valley" lines and (b) ore following the steep crowded vein latitude contours.

No. 14 Vein.—This vein has been developed by drifting and diamond drilling between the 1,250- and 2,750-levels for a maximum length of 900 feet. It lies west and slightly north of No. 4 Vein and bears a strong resemblance to it. Quartz widths average probably slightly over a foot, although widths as great as two feet are common, and where "folding" has taken place the vein is as much as six feet wide. The vein has an average strike about three degrees south of east and a dip 85° south.

As can be seen in Figure 1A, though the vein strikes slightly south of east it crosses the strata from north to south as it goes west and down the dip. This feature, together with the S-shaped vein "fold," is the reason for classifying the vein as belonging to Group 1.

It starts at its east end as a small quartz thread or stringer along the porphyry-conglomerate contact and in a short distance becomes wider and ore bearing in the conglomerate, which is the host rock for the greater part of its length. Near the conglomerate-tuff contact the vein pinches out but another, still called No. 14, commences as a stringer a few inches to a few feet south. This becomes average vein size until it reaches the tuff-conglomerate contact where it widens, describes an S-shaped "fold" and continues westward in the tuff formation. Fifty to two hundred feet west of the "fold" the vein narrows, becomes more glassy, and finally not ore bearing.

Contour Section No. 14 Vein.—(Fig. 4.) Because the vein lies between Shaft No. 3 and Shafts No. 2 and 4 in a part of the mine where no other mining has been done it was thought that the ground would stand well enough to mine the ore by shrinkage methods, using a 250-foot level interval rather than the customary 125-foot interval. Since all the stopes at the O'Brien Mine are surveyed only by tape and hand level, the lack of accurate inter-level surveys has necessitated contouring vein latitudes by interpolation between levels. With a level interval of 125 feet the contours can probably be drawn sufficiently well for all practical purposes but in the case of No. 14 Vein where double the customary level interval is used the accuracy of the contour pattern is open to question.

Mining of No. 14 Vein is still in the early stages for no stope extends for more than half way to the next level. Of the 877,500 square feet of vein area outlined on Figure 4, the area that has been mined, up to May 1950, amounts to about 124,400 square feet, or less than 15 percent of the total. Stope sampling is normally done only at the ends of stopes or where a decrease in mineralization suggests a lowering of the ore grade. For these reasons it is plain then that the ore boundaries shown on Figure 4 are only approximate. It is to be expected that the correlation of vein attitude and vein grade will not be as good as it is for the other veins that have been mined extensively.

Figure 4 shows the ore as a single shoot above the 1,500-level below which it splits into three and then four branch shoots. The westernmost shoot extending from the 1,750- to the 2,750-level between departures 450 W and 100 E splits below the 2,250-level into two distinct shoots. Taken as a whole the shoot is characterized by contours with an attitude more nearly horizontal than those to the east of departure 200 W. That is, the average vein strike within the shoot is left hand relative to the area to the east.

Above the 2,250-level the ore has been localized in part by the "fold" in the vein with the vein attitude, in detail, playing little or no part. Below the 2,250-level the west branch shoot follows a portion of the vein with a left-hand strike and steep dip. The east branch shoot is confined to the "folded" part of the vein. In the vicinity of this "fold," both below and above the 2,250-level, No. 14 Vein is richer than at any other place explored to date. Ore limits to the west are fixed by a pinching out of the vein.

From just below the 1,500-level to the 2,250-level, between departures 100 W and 200 W, there is a shoot of better-than-average grade that merges below the 2,000-level with the shoot just discussed. It is joined above the 1,750-level by another shoot that extends down to the 2,750-level between departures 100 W and 300 E. Both of these shoots appear to follow a part of the vein that has a right-hand strike with respect to the areas to the east and west, yet they occupy an area somewhat less than half of the total area characterized by a right-hand strike. No features have been recognized that would account for the increase in ore tenor within the shoot boundaries.

The largest shoot, although not the richest, extends from above the 1,375-level to the 2,750-level, between departures 0 E and 450 E. The shoot as a whole is characterized by flat contours as compared to the area immediately to the west. That is, the favorable vein strike is left hand. Dips are some-

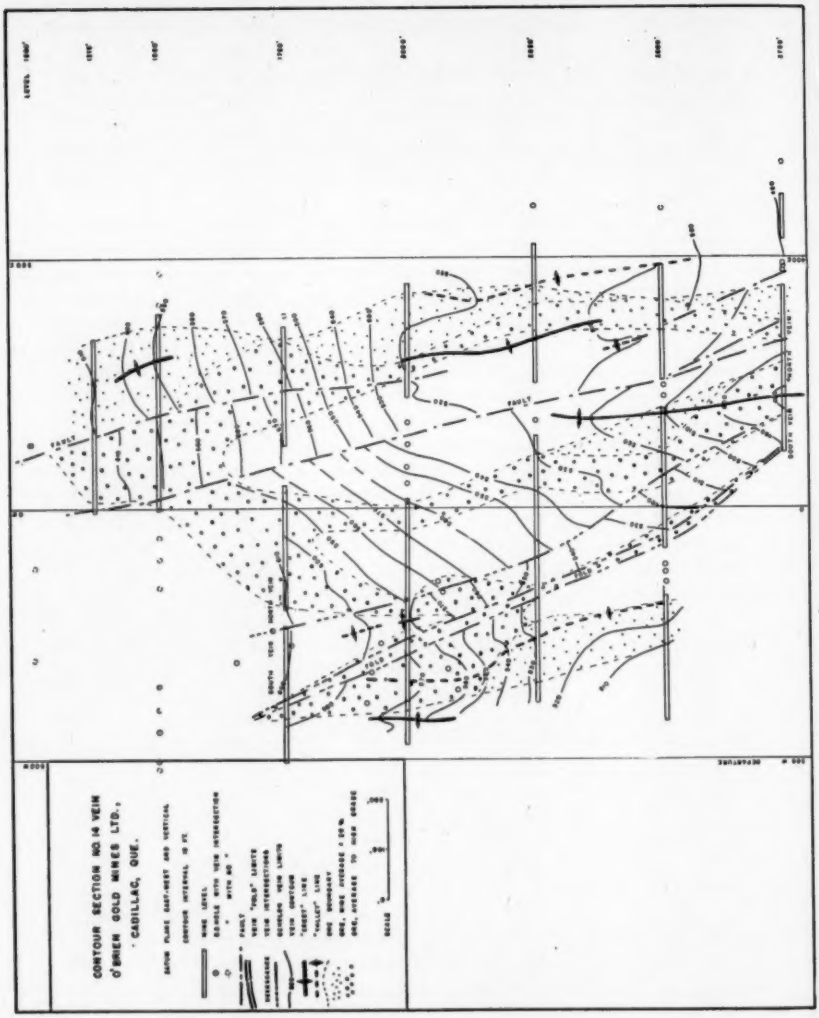

CONTOUR SECTION NO 14 VEIN
O'BRIEN GOLD MINES LTD.,
CADILLAC, QUE.

FIG. 4.

what flatter than average. From the 2,000-level to the 2,500-level that shoot is confined entirely to a part of the vein bounded by a "crest" line to the west and a "valley" line to the east where the strike is decidedly left hand. Below the 2,500-level the ore lies within an area with a left-hand strike, although it occupies only about half of this presumably favorable area.

In summary, then, it appears that the bulk of the ore in No. 14 Vein follows those portions of the vein where strikes are left hand and dips are slightly flatter to the south than average. Areas with average strikes of a right-hand nature, however, can not be ignored since sizeable ore shoots occur within these too. The richest ore is within a portion of the vein that displays an S-shaped "fold" pattern at the tuff-conglomerate contact.

Group B.

No. 1 NW-SE Vein.—This vein has an average strike between three and ten degrees north of west, and almost a vertical dip. Since the vein has a more northwesterly strike and a steeper dip than the south-dipping host rocks, it passes, from west to east and up the dip, from conglomerate, through tuff and some greenstone to the south andesite porphyry formation. Its intersection with No. 1 NE-SW Vein is shown on Figure 5 near departure 1,700 E. This intersection falls at the conglomerate-tuff contact except below the 2,625-level where the vein junction is in the tuff a few feet south of the formation contact and on the 1,875- and 2,000-levels where it is in the conglomerate. In the conglomerate, to the west of this vein intersection, the vein rarely exceeds a few inches in width and the combined widths of vein and wall rock alteration average less than one foot. Information on the vein in this area has been obtained largely from diamond drilling though some drifting and mining have been done immediately west of the intersection with No. 1 NE-SW Vein. Though the vein has not been drifted through as far as No. 4 Vein to the west, it is believed that it does continue and joins No. 4 at about the position of the line of X's shown in the lower left hand side of Figure 5. Branch veins and an increased width and grade of No. 4 Vein at the andesite porphyry-conglomerate contact fall about on the projection of the strike of No. 1 NW-SE Vein to the northwest. East of the intersection with No. 1 NE-SW Vein and below the 2,250-level the vein is well developed in tuff as far as the contact of the tuff with the south andesite porphyry formation. At this east end the vein describes a series of Z-shaped folds in the tuff and the porphyry immediately adjacent to their contact. The vein pinches out in the porphyry and as far as is known does not continue any more than a few feet in this rock. Abundant coarse gold occurs in the fractured quartz in the vicinity of the folding. A similar type of vein fold occurs in the unfolded tuff from the 750- to 1,875-levels as shown on Figure 5. It is thought to be localized by the intersection of the vein width with the contact of well-bedded tuff and an interbed of greenstone or chloritized andesite. Two other small folds of the Z-type occur between the 1,750- and 2,000-levels and from the 2,625- to 2,875-levels. These occur at the conglomerate-tuff contact where there is a sharp change in the plunge of the intersection of the vein with the No. 1 NE-SW Vein.

FIG. 4.

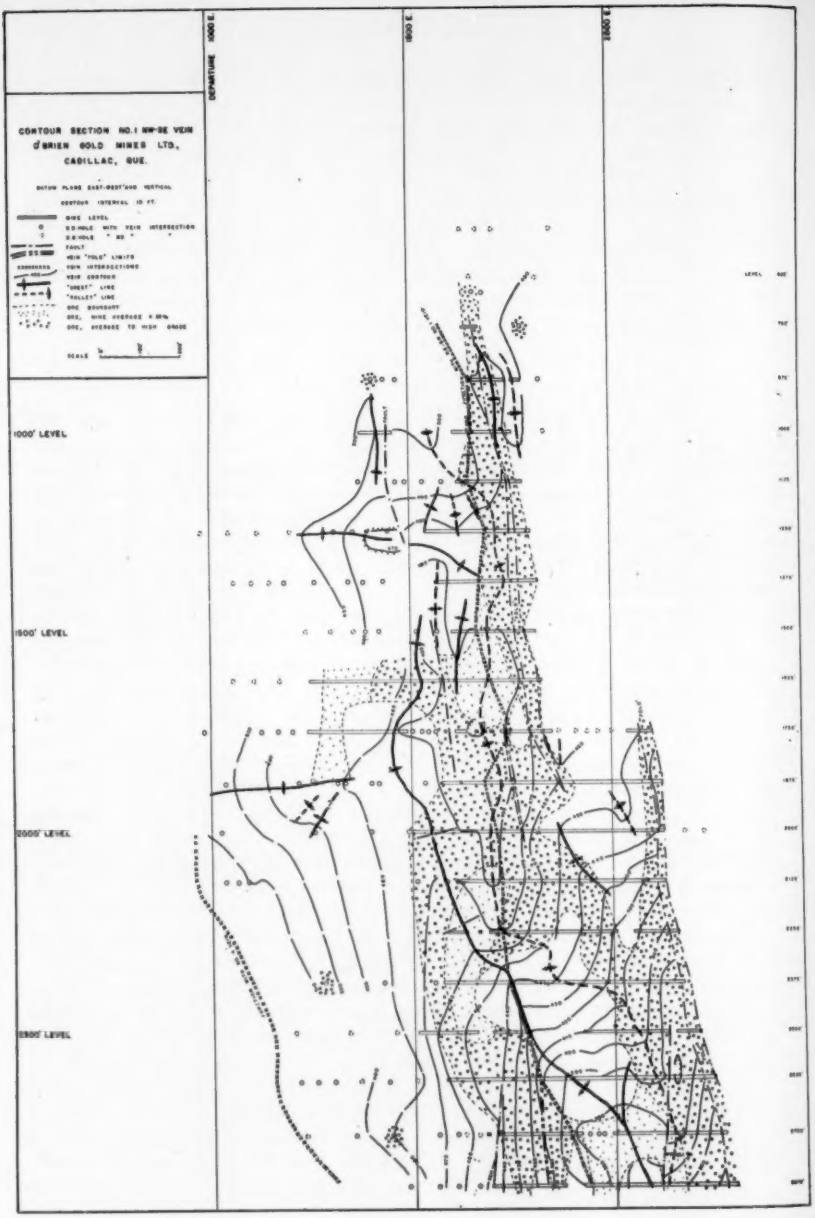

CONTOUR SECTION NO. I NW-SE VEIN
O'BRIEN GOLD MINES LTD.,
CADILLAC, QUE.
DATUM PLANE EAST-WEST AND VERTICAL
CONTOUR INTERVAL 10 FT.
DIVE LEVEL
D.D. HOLE WITH VEIN INTERSECTION
D.D. HOLE " NO "
FAULT
VEIN "FOOT" LIMITS
VEIN INTERSECTIONS
VEIN CONTOUR
"CREST" LINE
"TROUGH" LINE
ORE BOUNDARY
ORE, MINE AVERAGE
ORE, AVERAGE TO HIGH GRADE
SCALE
DEPARTURE 1000 E.
1500 E.
2000 E.
1000' LEVEL
1500' LEVEL
2000' LEVEL
2500' LEVEL

FIG. 5.

No. 1 NW-SE Vein diminishes in length and width above the 875-level. Diamond drilling and crosscutting as far south as and beyond the south porphyry formation above the 625-level have failed to locate any expression of the vein.

Contour Section No. 1 NW-SE Vein.—As can be seen from a study of Figure 5 there is an ore shoot of major importance extending from the 750-level to the deepest workings on the 2,875-level. From the 750-level to the 1,625-level the ore shoot has a chimney-like form where it is chiefly confined to the area between the junction with No. 1 NE-SW Vein and the big fold to the east. A "valley" line near the west boundary of the shoot indicates that the strike of the vein throughout most of the shoot is right hand relative to the strike to the west of the ore. Below the 1,500-level the shoot broadens abruptly and below the 2,000-level it is divided into three shoots having the pattern of a crude N on the longitudinal section. The positions of the three shoots coincide very well with those portions of the vein that have steep dips and strikes which are right hand, as indicated by steep, closely-spaced contours, (1) immediately west of a pronounced "crest" line, (2) immediately east of a pronounced "valley" line and (3) within a Z-shaped vein fold. Low-grade and waste areas coincide with those parts of the vein which have relatively flat south dips and left hand strikes. This is well shown in Figure 5. The broad ore zone between the 1,500- and 2,250-levels extends for roughly an equal distance on each side of the "valley" line and consequently does not fit the favorable right hand strike picture. Recent stoping has indicated the presence of a series of en échelon post-vein, pre-ore mineralized reverse faults, within this area, which displace the ore vein from a few inches to thirty-five feet up the dip of the fault. These faults dip from 60° to 80° north and strike within 10 degrees of the vein strike and are mineralized with quartz and free gold. Although they are seldom more than a few inches wide they appear to have enriched the ore veins to a considerable extent. The traces of the intersection of two such faults with the No. 1 NW-SE Vein are shown on Figure 5, at or near the west end of the 2,000- and 2,250-levels.

Below the 1,875-level between departures 1,000 and 1,500 E diamond drilling indicates that vein contours must be steep but no amount of ore has yet been found. The spacing of the contours would not appear to be as close as the spacing in the richer parts of the ore shoots to the east so that on the whole the strike of the vein in this little-explored section is probably left hand relative to the strikes farther east. It is quite possible that closer drilling or drifting would indicate a closer spacing of the contours in some parts and a greater spacing in other parts of this lean area, with better gold values following the closely spaced contours.

Two small areas within the vein do not conform to the favorable strike and dip explanation. From the 1,000- to the 1,250-level between departures 1,300 and 1,400 E a limited amount of drifting and diamond drilling indicate the presence of a steep "crest" line but except for one interesting drill hole intersection no ore has been found along its west side where the strikes are relatively right hand and the dips are steep. Between the west ends of the 1,375-

and 1,500-levels vein strikes are right hand but no ore is indicated on either level by drifting. No explanation is known for these two exceptions.

No. 9 Vein.—Number 9 Vein strikes between east-west and 10 degrees south of east and has an average dip of 85° north. The vein describes a series of Z-shaped folds where it joins No. 4 Vein to the east. Similar "folding" is present above the 1,875-level where the vein terminates to the west against a series of graphitic, argillaceous sediments and to a lesser extent below the 1,750-level where it splits into a north and south branch. Development above the 1,375-level indicates that the strike of No. 9 Vein approaches parallelism

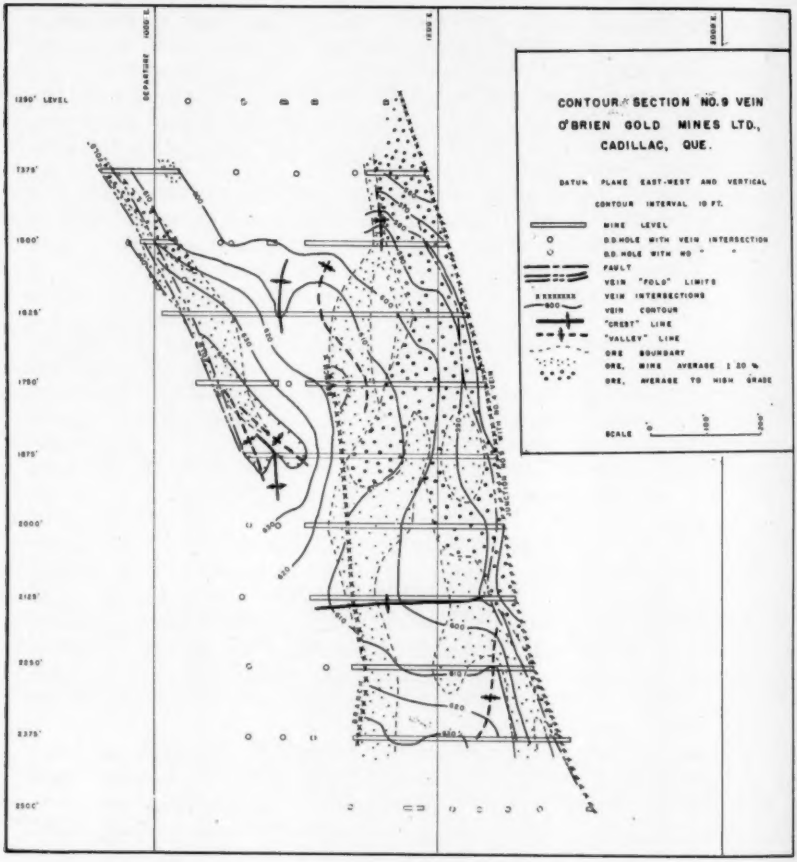


FIG. 6.

with No. 4 causing it to merge with No. 4. Between the 2,375- and 2,500-levels the vein bottoms against the Cadillac Shear Zone.

In a mine with characteristically narrow vein widths No. 9 Vein is a welcome exception. Throughout the greater part of its length the vein is rarely less than a foot wide and mostly retains a width of 2.5 to 3 feet. The graywacke country rock is characteristically altered to a brownish color for a distance from the vein at least as great as the vein width. This altered rock contains an abundance of small quartz stringers, disseminated arsenopyrite and a seal-brown biotite. Stoping widths are seldom less than four feet and where "folding" is present ore widths are as great as twenty feet. Visible gold is common in the "folded" areas.

Contour Section No. 9 Vein.—By referring to Figure 6 it can be seen that there are two major ore shoots in No. 9 Vein, a large one on the east and a small one to the west. The larger one is limited to the east by the junction of No. 9 and No. 4 Veins. It terminates to the west along steeply pitching synclinal axes or "valley" lines or at the intersection of No. 9 with a branch vein of more southwestwardly strike. The richest part of the shoot is along its east boundary within the "folded" area and extends to the west in the upper half where contours remain steep and relatively closely spaced. Below the 2,000-level the contours spread apart with a corresponding drop in grade of the ore. An abrupt flattening of the contours below the 2,125-level coincides with the bottoming of the ore shoot except for a low grade section adjacent to the branching of No. 9 referred to above.

The smaller shoot to the west coincides with a plunging Z-shaped vein fold. Strikes within the ore shoot are right hand with respect to the barren portion of the vein to the east. The shoot bottoms about the 1,875-level where the contours flatten and the fold dies out. It terminates to the west due to the fact that the vein folds against a graphitic and argillaceous sedimentary bed and ends there.

Ore shoots in No. 9 Vein seem to have been localized by (1) vein "folds" at vein junctions and highly dissimilar rock strata contacts, (2) right-hand strike directions as indicated by the presence of ore to the east of steeply plunging "valley" lines, especially where contours are crowded, and (3) branching veins.

SUMMARY AND CONCLUSIONS.

In the following table the results of the study of the vein contour sections have been tabulated. The first two columns list the vertical extent of the ore shoots by levels and the lateral extent of the shoots by departures. The last six columns list the structural features of the veins that may have influenced the localization of the ore, namely, strikes which are relatively left hand, strikes which are relatively right hand, dips steeper than average, dips flatter than average, vein junctions or branches and "folds." A double XX indicates a close correlation of the ore with that particular structural feature and a single x indicates some correlation between the ore and this structure though the ore shoot is frequently of poorer grade and the correlation much less perfect.

	Vertical Extent	Departures	Strike		Dip		Vein Jct.	Fold
			Left	Right	Steep	Flat		
Group A								
No. 1 NE–SW	Surf.– 500	200– 300 E	XX			XX		
	Surf.– 300	500– 800 E	XX	x		XX		
	Surf.– 625	950–1,550 E	XX	x				
	750–2,875	1,600–2,000 E	XX		XX		XX	
	1,125–2,375	1,000–1,660 E	XX	x		x		
	2,500–2,875	1,800–2,100 E	XX					XX
No. 4	Surf.– 750	1,500–1,800 E	XX	x	XX			
	750–1,375	1,400–1,500 E	x				XX	
	1,500–2,500	1,350–1,800 E	XX		XX		x	
	2,000–2,750	900–1,100 E	XX					
	Surf.– 750	950–1,200 E	XX	x		x		
	750–1,375	1,000–1,150 E	XX					
	750–1,375	900–1,000 E		XX				
	1,875–2,125	1,250–1,300 E	XX					
	1,250–1,500	650– 750 E			XX			
No. 14	1,750–2,750	450 W– 100 E	XX	x		x		XX
	1,500–2,250	200 W– 100 W		XX				
	1,500–2,750	100 W– 300 E		XX				
	1,250–2,750	0 W– 450 E	XX			x		
Group B								
No. 1 NW–SE	750–1,625	1,600–1,900 E		XX	XX		x	XX
	1,625–2,250	1,500–1,950 E			x		XX	XX
	2,250–2,875	1,500–1,850 E		XX	XX		x	x
	1,750–2,875	1,950–2,300 E		XX	XX			XX
No. 9	1,250–2,375	1,300–1,700 E		XX	XX		XX	XX
	1,375–1,875	900–1,200 E		XX				XX

A glance at the table shows that, in the veins of Group A, by far the majority of the ore shoots are characterized by left-hand strikes. Vein junctions and "folds," when present, show a good correlation with the shoots. There is little or no correlation between vein dips and ore shoots.

The tabulation for the veins of Group B shows that all the ore shoots, except one, are characterized by right-hand vein strikes and all but one by dips that are steeper than average. All of the shoots have been influenced to a greater or lesser degree by vein junctions or vein "folds."

ACKNOWLEDGMENTS.

The writer wishes to express his thanks to Mr. H. E. Sparks, Manager, O'Brien Gold Mines, Limited, for permission to publish this paper.

O'BRIEN GOLD MINES, LIMITED,
KEWAGAMA, P. Q.,
July 5, 1950.

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SIGNIFICANT REPLACEMENT TEXTURES AT COBALT AND SOUTH LORRAINE, ONTARIO, CANADA.

EDSON S. BASTIN.

ABSTRACT.

Results of a restudy of superior polished specimens of representative nickel-cobalt-silver ores from Cobalt and South Lorraine, Ontario, are presented in seventeen paragenetic diagrams. Typical textures such as tubercle texture, rhythmic banding and dendritic texture are described and are interpreted as replacement textures developed through the diffusion of mineralizing solutions of changing compositions through highly calcitized wall rocks.

The unusual characters of irregular veinlets of silver that traverse some of the arsenides in all directions are interpreted as indicating that they are fillings of ruptures produced by hydraulic pressures within the mineralizing solutions and potentially operative in all directions.

The late stages of mineralization were characterized by extensive and varied replacements of early ore minerals by later ones. Silver was the mineral most abundantly replaced and calcite the principal replacing mineral. Thus the closing episode of the mineralization reversed the order of the initial phase in which silver abundantly replaced calcitized wall rocks.

INTRODUCTION.

THE cobalt-nickel-silver type of ore deposit though no longer of great economic importance is still of much scientific interest because of its unusual mineral composition and its unusual textures which have been difficult to interpret. Although a relatively rare type its world wide distribution has presented interesting problems in supergene versus hypogene ore deposition and in genetic relations to basic versus acid intrusives.

Since 1917 the writer has published several papers dealing with this ore type which are listed in the bibliography at the end of this paper. Numbers in parentheses in the present paper refer to these earlier papers. The latter contain many references to other authors.

Evidence was found in the Miller Lake–O'Brien mine in the Gowganda district, Ontario, in 1948 of wide spread replacement of silver dendrites by calcite late in the primary mineralization (5).[1] Replacement of silver dendrites by calcite and, less commonly, by other minerals was described by Zuckert in 1925 (8, p. 105) in ores from Joachimsthal in Bohemia. In 1931 the German geologist, Keil (7, Fig. 49; 6, Pl. 14, Fig. 2) described replacement of silver dendrites by calcite in ores from Cobalt, Ontario. As such replacements had not been described by American authors from the ores of Cobalt and South Lorraine, Ontario, it seemed desirable to restudy specimens from these camps to see whether such replacements were common. The specimens examined were

[1] Numbers in parentheses refer to Bibliography at end of paper.

FIG. 1. Silver dendrite enveloped in lollingite. Black is calcite matrix.

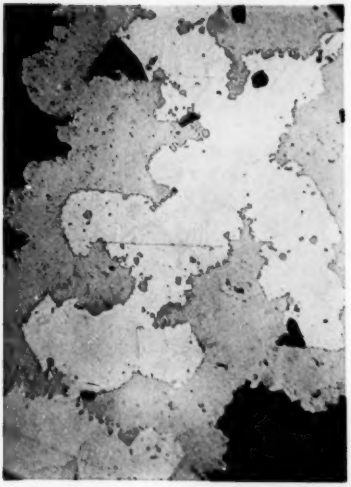


FIG. 2. Silver dendrite in lollingite; younger calcite replacing silver at tips of dendrite (black triangles).

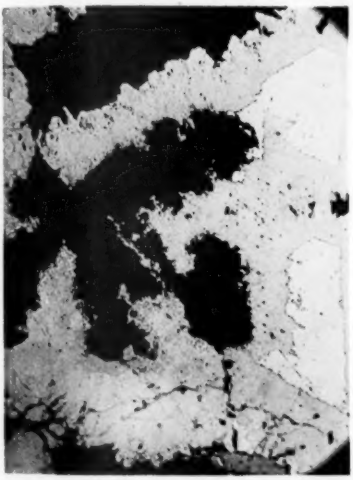


FIG. 3. Dendrite, originally silver (white), now largely replaced by younger calcite (black). Gray is lollingite.

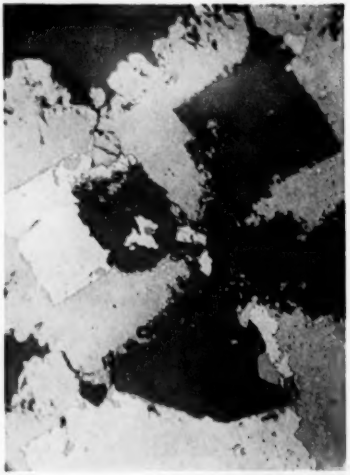


FIG. 4. Cruciform dendrite now mainly younger calcite (black). Original silver (white) forms tips of two arms, and three remnants to left of center of cross.

FIG. 5. Dendrites originally silver, almost wholly replaced by younger calcite (black) with irregular remnants of silver (white).

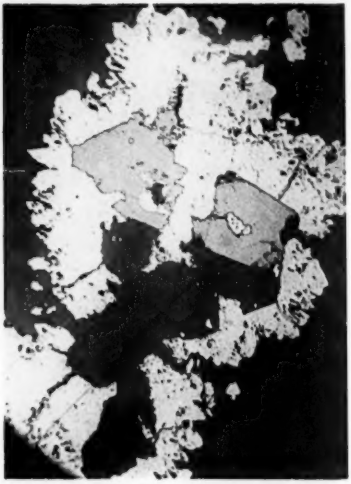


FIG. 6. Dendrites originally silver, replaced first by argentite (gray), in turn replaced by younger calcite (black).

FIG. 7. Dendrite now largely argentite (dark gray) in lollingite envelope (light gray). Small replacement remnants of silver (white) occur within argentite. Calcite (black) beginning to replace argentite at ends of short arms.

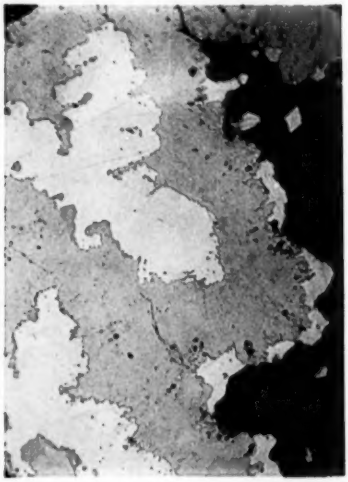


FIG. 8. Dendrites of silver (white) in lollingite (gray). Younger silver occurs between lollingite envelope and matrix of older calcite.

Figures 1–8 from the Casey mine, Cobalt. X 90. Spec. 75.

mainly collected by the writer many years ago and are in the University of Chicago collections. New and excellent polished specimens of many of them were prepared by C. S. Fletcher of North Cambridge, Mass. The writer is indebted to Prof. A. L. Anderson of Cornell University for providing laboratory facilities for their study.

PARAGENETIC TABLES.

As the mining camps of Cobalt and South Lorraine are 16 miles apart the paragenesis of their ores will be shown in separate tables. The composite diagrams for the two districts are nearly identical.

Several textural types are represented in the collection studied which are listed below with their specimen numbers. The first two types are the commonest.

Massive lollingite and cobaltite veined with silver: Nos. 1, 2, 4, 5, 6, 217.
Tubercle texture: Nos. 7, 35, 77, 79, 206, 211, 214, 215.
Rhythmic banding: No. 216.
Dendritic texture: No. 75.
Veins: No. 213.

The seven South Lorraine specimens are all from the Frontier mine, now defunct. The ten specimens from Cobalt are from four mines which are listed in the paragenetic table. All specimens are high grade silver ores except Nos. 35 and 216 which show no silver minerals.

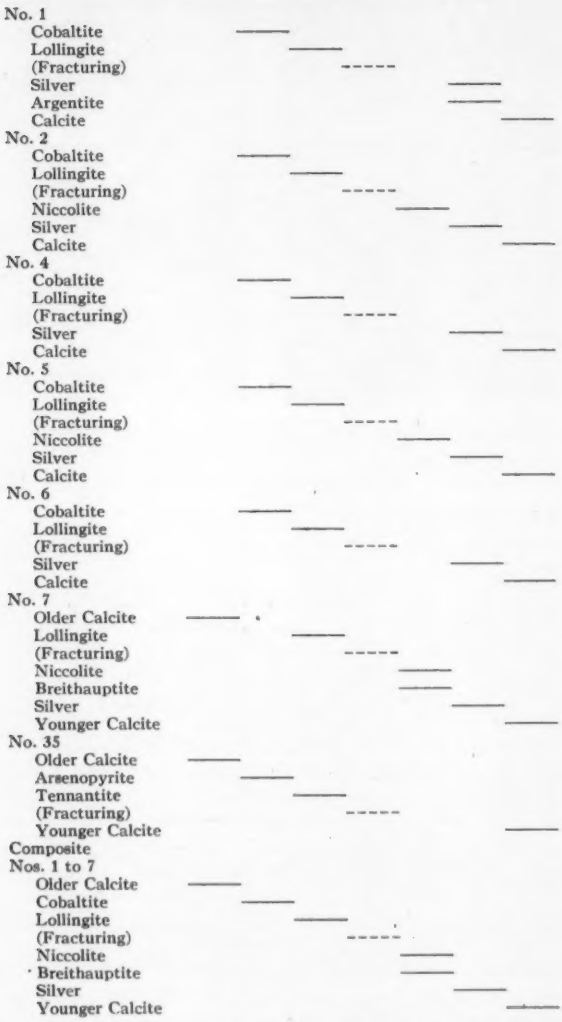
TEXTURAL TYPES.

Massive Lollingite and Cobaltite Veined with Silver.—The most notable textural feature of this type is the extreme irregularity of most of the fracturing (Fig. 12; 3, Pl. IV A). The causes of the fracturing are considered in the section on fracturing. The fractures are occupied by silver and calcite commonly with minor amounts of niccolite and breithauptite.

Tubercle Texture.—The name tubercle texture was proposed by the writer in 1925 (3, p. 11) for textures common in many of the ores of the cobalt-nickel-silver type, not only in Canada but in other parts of the world, in which the metallic components lying in a non-metallic matrix somewhat resemble clusters of grapes or of tubercles. Typical clusters from Cobalt and South Lorraine are illustrated in an earlier paper (3, Pl. II). They are interpreted as a replacement texture developed by diffuse penetration of mineralizing solutions through highly altered wall rocks. Generally the individual tubercles can be differentiated into rim and core but this is not always possible. In the simplest case (3, Pl. II B) the rim is composed of a single mineral and the core, like the matrix outside, is of non-metallic minerals, generally calcite. In most tubercle ores, further flow outward from the diffusion centers has replaced the calcite of the cores by metallic minerals mostly different from those of the rim. In most of the tubercle ores of Cobalt and South Lorraine the rim minerals are lollingite and cobaltite and the core minerals are niccolite and/or breithauptite, native silver, and calcite. Evidence is conclusive that the core

TABLE 1.

PARAGENESIS AT FRONTIER MINE, SOUTH LORRAINE.



Note: To facilitate comparisons and the construction of the composite diagram, minerals are placed in the same vertical columns throughout the series. Horizontal gaps in any diagram have therefore no time implications. No. 35 was not included in the composite because the age relations of arsenopyrite to cobaltite and of tennantite to lollingite are not precisely known.

minerals are younger than the rim minerals. One such piece of evidence is the presence of a few veinlets of the core minerals traversing the rims; another is the occasionally observed continuity of core silver across the rims with silver outside the rim (3, Pl. III B and C).

An unusual variant of the ore from the Frontier mine shows typical tubercle texture but the rims are arsenopyrite and the cores are tennantite (3, Pl. II C).

Rhythmic Banding.—Rarely the tubercle ores show rhythmic alternations of two metallic minerals within the tubercles. Low grade ore from the Penn-Canadian mine at Cobalt shows no demarkation into core and rim. At the center is (1) lollingite with scattered cobaltite crystals; enclosing this as successive bands are (2) cobaltite, (3) lollingite, (4) cobaltite, (5) lollingite, (6) cobaltite, and (7) lollingite. The cobaltite is automorphic against the lollingite on both the outside and the inside of each cobaltite band. The outermost band in every tubercle is lollingite. This texture is interpreted as diffu-

TABLE 2.

PARAGENESIS AT COBALT, ONTARIO.

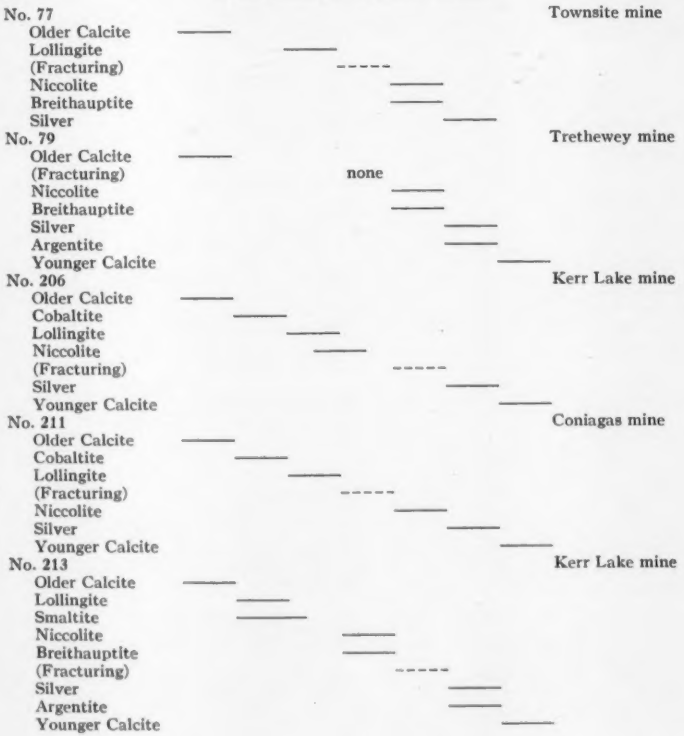
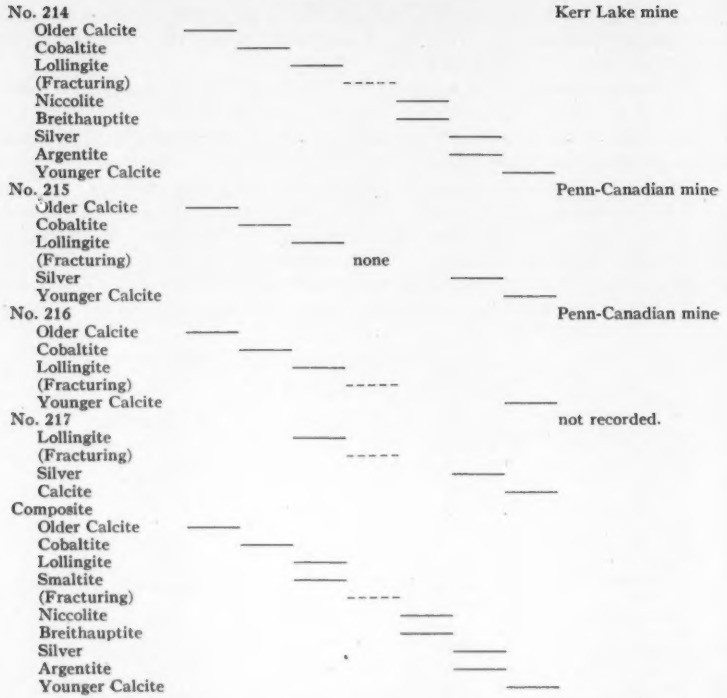


TABLE 2.—*Continued*



Note: To facilitate comparisons and the construction of the composite diagram, minerals are usually placed in the same vertical columns throughout the series. Horizontal gaps in any diagram have therefore no time implications.

sion banding and seems best explained as indicating first the deposition of bands of cobaltite in a calcitic matrix, and second the replacement of the calcite interspaces by lollingite. Veinlets of younger calcite traverse all these bands and send off branches parallel to some of them.

Dendritic Texture.—In a paper published in 1949 (5) the writer presented evidence that silver dendrites or skeletal crystals in ores from the Miller Lake–O'Brien mine in Gowganda had been extensively replaced by calcite late in the mineralization process. The restudy of representative specimens from Cobalt and South Lorraine to see whether late calcite replacements were also present in them has been the principal object of the present paper. Dendrites are particularly valuable in the secure identification of replacement because they display the characteristic crystal forms of native silver. The preservation of that form even though other minerals have taken the place of all or a part of the silver is one of the best evidences of replacement. Pseudomorphism in general

is one of the most secure evidences of replacement, although in places accomplished by the filling of open spaces. Typical dendrites are displayed in a single specimen from vein No. 5 in the Casey mine at Cobalt (Spec. 75). Four polished specimens were prepared from this specimen and from these many of the illustrations of this paper were taken. The paragenetic sequence in this specimen is shown in Table 3.

Niccolite, a minor component of the dendrites, is most abundant near their peripheries. It is generally automorphic against silver but very exceptionally the reverse is the case. All silver except that forming the dendrites appears to be younger. This is most obviously true of that occurring between the lollingite and the older calcite and conforming to the crystal outlines of the lollingite (Fig. 8). Silver forming veinlets wholly within the older calcite is probably also younger silver.

There has been much diversity of opinion concerning the origin of the dendritic crystalline forms displayed by the silver. They have been attributed not only to the silver but by one or another observer to nearly all of the minerals that in various occurrences sheath the silver or have replaced it (6, pp. 44–46).

TABLE 3.

PARAGENESIS. DENDRITIC ORE FROM CASEY MINE, COBALT, ONT. (SPEC. 75).

Older Calcite	———
Older Silver	——— as dendrites
Cobaltite?	——— very minor
Niccolite	———
Lollingite	———
Younger Silver	———
Argentite	———
Younger Calcite	———

Out of this confusion of explanations as a result of more detailed studies several facts become obvious: 1) in ores of the type under consideration native silver is clearly the dominant dendrite mineral; 2) the forms of the silver dendrites are isometric and no non-isometric mineral can be held responsible for them; 3) dendrites in these ores that have the forms of silver dendrites but are composed of one or more other minerals can be shown to be replacements of silver dendrites (3, pp. 16–17; 5, pp. 441–442).

In dendritic ore from the Casey mine at Cobalt successive stages in the replacement of silver dendrites by calcite and less commonly by argentite are shown in Figures 1 to 5. Figure 1 shows a single silver dendrite in its unaltered form with the usual sheath of lollingite. The cross-like form of the silver is characteristic. Some of the boundaries of the silver are straight crystal faces; the irregularity of other boundaries are due in part to small niccolite areas at or near the silver peripheries. In Figure 2 replacement of the silver by calcite (black) has begun at the tips of two dendrite arms. In Figure 3 most of a cruciform dendrite of silver (white) has been replaced by calcite (black). In Figure 4 most of another dendrite of silver (white) has been replaced by calcite (black). The calcite commonly shows automorphic outlines against the silver that it has replaced as shown particularly in the lower arm of the

cross. Three remnants of silver can be seen isolated within the replacing calcite. In Figure 5 nearly all of a group of silver dendrites has been replaced by calcite (black). In the calcite a number of silver remnants remain.

Although calcite was the principal mineral to replace the silver it was not the only one. In Figure 6 a silver dendrite has first been replaced by argentite (gray), which contains two irregular replacement remnants of silver. The argentite has in turn been replaced by calcite (black), which connects at several points with the calcite of the matrix. The replacing calcite shows straight automorphic outlines against the argentite. Figure 7 shows a dendrite in which silver has been replaced almost entirely by argentite (gray). Numerous small irregular remnants of silver (white) remain within the argentite. Particularly in the two shorter arms of the dendrite replacement of argentite by calcite (black) is well advanced. In the same specimen a few dendrites of a second gray metallic mineral occur that have also been formed by the replacement of silver. This mineral has a hardness of 3.5, is isotropic and shows dark resin-colored internal reflections. It is tentatively identified as sphalerite.

Replacement of silver dendrites by calcite, argentite, proustite, and even by chalcocite and chalcopyrite seems to have been first recognized by Zuckert (8, p. 105) in 1925 in ores from Joachimsthal in Bohemia. Replacement of silver dendrites by calcite in the ores of Cobalt, Ontario, seems to have been first figured and described by the German geologist Keil in 1931 (7, Fig. 49; 6, Pl. 14, Fig. 2).

TEXTURAL AND GENETIC RELATIONS.

In describing the relationships of the ore components the Cobalt and South Lorraine districts will be considered as a unit.

Older Calcite. This mineral is observable in those specimens showing tubercle and dendritic textures. It forms the matrix of these textural forms and seemingly represents highly calcitized wall rock into which the mineralizing solutions diffused to develop these textural features. Tests show that much of this calcite is slightly ferruginous.

Cobaltite. This mineral is not found in all specimens; when present it is very subordinate to lollingite. It was generally the first metallic mineral to be deposited, being automorphic with respect to all other minerals of the ores. In one specimen (Spec. 211) cobaltite and lollingite seem to be about contemporaneous each in places conforming to the crystal outlines of the other.

Lollingite. This is the dominant metallic in nearly all of the specimens studied. Prismatic, anisotropic, polarization colors steel-blue to salmon pink.

Fracturing. As most of the fracturing observed in the ores occurred after the deposition of lollingite the process will be considered at this point, which corresponds to its usual position in the paragenetic diagrams. In the Kerr Lake mine one specimen shows fracturing in its normal position preceding the deposition of niccolite and breithauptite whereas in two other specimens the deposition of these minerals preceded the fracturing. The irregularity of the fracturing as shown in a polished specimen from the Kerr Lake mine at Cobalt has been figured in a previous paper (1, Pl. VII, Fig. A). Most of the fractures are now occupied by silver or calcite or by segments of both minerals;

niccolite and/or breithauptite may be minor components. Some of the narrower veinlets have walls that match and may therefore be regarded as normal fracture fillings. Most of the veinlets have walls that do not match and for this reason were earlier interpreted by the writer as replacement veinlets. This explanation had, however, to be abandoned when it was found that the walls of the irregular veinlets were mostly formed of crystals of the bordering arsenides whose straight, smooth outlines showed that they could not have been attacked by replacement (3, Pl. V-A, V-B; 6, Pl. 5, Figs. 1, 2). The veinlets are indubitably fracture fillings for they grade in places into breccias as shown in Figure 12. They are, however, of a peculiar type because they are generally extremely irregular in form, commonly changing abruptly in width, and are very diverse in direction. The walls of most of them are crystal faces of the bordering arsenides. Moreover, incomplete filling of the fractures seems never to occur and the walls of the veinlets are tight as shown by the fact that replacement of the silver by calcite does not penetrate preferentially along the walls but is spread over the entire width of the veinlet to produce "segmented" veinlets. The peculiar features of these veinlets seem best harmonized by the interpretation that they occupy ruptures produced and enlarged by the pressure of the mineralizing solutions which was operative while crystallization of the arsenides was still in progress and which could exert their hydraulic pressure in any direction. This concept makes it easier to understand also the delicate minuteness of some of the silver veinlets as shown in Figure 10.

Niccolite and Breithauptite. Commonly after the fracturing, rarely before, niccolite was deposited, in places accompanied by breithauptite. In some specimens these minerals are absent and the fracturing was directly followed by silver deposition. Niccolite and breithauptite seem to be of the same age. Crystals of each indent the other but there are no veinlets of one in the other. They are common but minor components of the silver veinlets and dendrites, and of the silver bearing cores of tubercles. With rare exceptions they are automorphic against the silver and, therefore, slightly older.

Silver. The relatively rare dendritic occurrences of silver have already been described. In them the silver was clearly the first metallic mineral to be deposited. Other silver is younger than that of the dendrites; it fills small fractures in the lollingite or occurs between lollingite and the calcite matrix. Silver traversing the calcite matrix but having no sheath of lollingite and having the form of veins rather than dendrites is also probably younger.

Silver occurs most commonly as: 1) a filling of what have been interpreted as dilation ruptures in lollingite and cobaltite, and 2) as a component of the cores of tubercles. Typical rupture fillings are shown in Figure 12; some are so small and delicate, as shown in Figure 10, that they could easily be misinterpreted as inclusions of older silver within the arsenides. High magnification shows, however, that each tiny silver area conforms to the crystal outlines of the bordering arsenides. Furthermore there are transitions from scattered "inclusions" to lines of "inclusions" to silver veinlets.

In a number of specimens showing tubercle texture, silver occurs not only in the cores of the tubercles but may also occur outside the tubercles between the lollingite and the older calcite of the matrix. This silver is of the same age

as that of the cores for not uncommonly it connects across the lollingite with that of the cores (3, Pl. 3B, 3C).

In the dendritic ore (Spec. 75) the silver that constitutes the dendrites is the oldest metallic mineral of the ore and is sheathed by lollingite. As shown in Figure 8, however, some silver is younger and occurs outside the lollingite sheath.

Where niccolite and breithauptite are present, silver nearly always conforms to their automorphic outlines. Rare instances of silver replacing niccolite will be described later.

Argentite. Partial replacements of native silver dendrites by argentite have already been described and are shown in Figures 6 and 7. Such argentite is older than the younger calcite that locally replaces it.

In the more common ore types some specimens show small amounts of argentite in all cases associated closely with native silver. Some argentite rims the silver but some also occurs in irregular areas within the silver. This argentite may be a replacement of the silver but the evidence is not conclusive.

Late Calcite. In contrast to the older calcite that forms the general matrix in which the metallic minerals have developed by processes of diffusion and replacement, other calcite is younger than all the metallic minerals of the ore. In the descriptions of dendritic textures evidence has been presented of replacement of native silver dendrites by calcite with the preservation of the original forms of the silver. Such pseudomorphism is the strongest evidence of replacement but other evidence, though less conclusive, is common in all of the textural types studied. Calcite is a component of the irregular veinlets that characteristically traverse lollingite and cobaltite. It is, therefore, younger than the calcite of the matrix in which, by replacement, the arsenides were developed. More rarely calcite veinlets traverse the core minerals of tubercles or follow around or skirt the borders of the cores. These relations show that the calcite in question is the youngest mineral of the ores.

Although it conforms to the crystal outlines of cobaltite and lollingite the late calcite shows its own characteristic crystal outlines against all the other metallic minerals. As it is younger than these minerals this can only mean that the calcite has replaced them automorphically. Replacement of silver by late calcite is particularly common. In a specimen from the Frontier mine (Spec. 4) there are zones in lollingite in which all of the irregular veinlets are of silver, whereas in the adjacent zones on each side the continuations of these veinlets are of calcite. Figure 12 shows these relations and one of the calcite zones shows brecciation. These relations are interpreted as indicating automorphic replacement of vein silver by calcite along zones rendered pervious by fracturing. Figure 13 shows veinlets traversing cobaltite and lollingite. These veinlets are believed originally to have been silver (white) but this mineral has been largely replaced by calcite (black) leaving behind, however, three irregular replacement remnants of silver. In the cores of tubercles from the Frontier mine (Spec. 7), as shown in Figure 14, breithauptite (light gray) has been automorphically replaced by acute crystals of calcite. Replacement of argentite in dendrites by calcite has already been described and is shown in Figures 6 and 7. Replacement of tennantite in a rare variety of tubercle ore from the

FIG. 9. Veinlets of younger silver (white) in older calcite outside lollingite (light gray) envelope of a dendrite. Casey mine. X 90.

FIG. 10. Small irregular veinlets of silver (white) in cobaltite and lollingite (gray). Frontier mine. X 90.

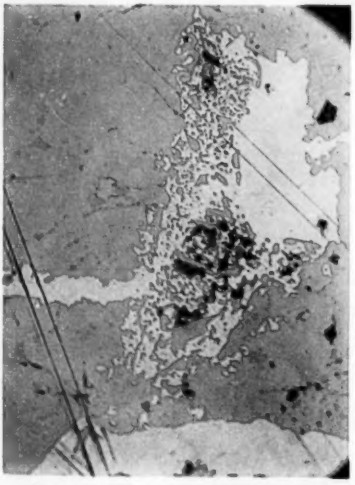


FIG. 11. Silver (white) in veinlets and as a matrix between small lollingite crystals, conforming to their crystal outlines. Frontier mine. X 90.

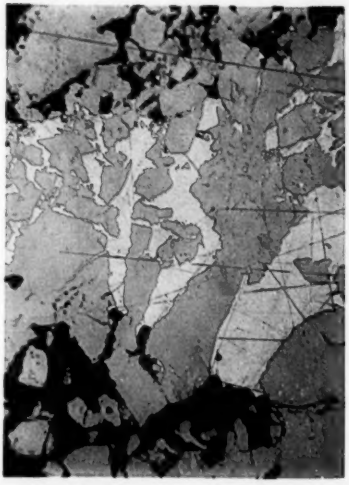


FIG. 12. Irregular veinlets of silver (white) in lollingite (gray). Younger calcite (black) has automorphically replaced the silver, but shows no preference for silver-lollingite contacts. Frontier mine. X 90.

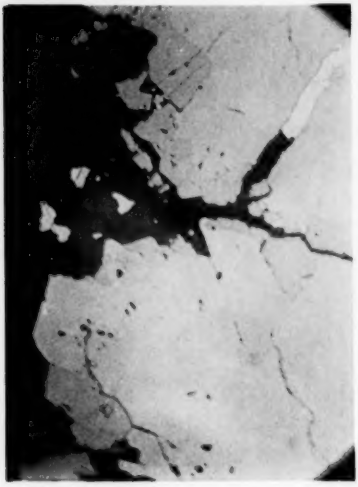


FIG. 13. Silver areas and veinlets (white) in cobaltite and lollingite (gray) partially replaced by younger calcite (black) with three remnants of silver at left. Frontier mine. X 90.

FIG. 14. Breithauptite (white) featheredged in process of replacement by prisms and acute crystals of calcite (gray). Frontier mine. X 90.

FIG. 15. Arsenopyrite (white) and tennantite (light gray), the latter selectively replaced by calcite (dark gray) leaving remnants. Frontier mine. X 90.

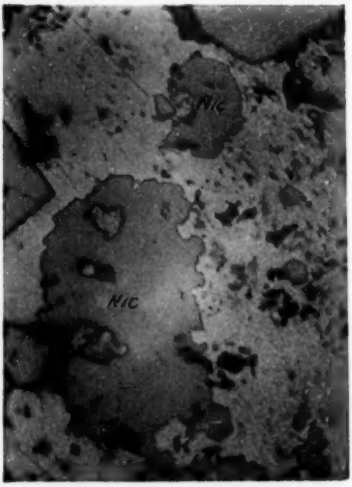


FIG. 16. Niccolite and smaltite (dark gray) in matrix of silver (lighter gray). Smaltite shows smooth crystal outlines not replaced by silver; niccolite ragged outlines indicate replacement by silver; black, younger calcite. Kerr Lake mine. X 90.

Frontier mine is shown in Figure 15, a multitude of irregular replacement remnants remaining. There is no doubt that the calcite is younger than the tennantite for in the same specimen rare veinlets of calcite traverse both tennantite and arsenopyrite. Some of these veinlets are narrow and parallel-walled in the arsenopyrite but expand into irregularly bulbous areas in the tennantite as a result of selective replacement.

Rare Replacements of Niccolite by Silver. In the laboratory the simple arsenides and antimonides of iron, cobalt, and nickel are effective precipitants of metallic silver from silver sulphate and silver bicarbonate solutions (1, pp. 228–233; 2, pp. 152–154). In the two papers just referred to the writer emphasized the possibility that such reactions may have been responsible for the deposition of much of the silver in these ores. It so happened that a number of the specimens studied and figured at that time were from the Kerr Lake mine and show what still appears to be valid evidence of replacement of niccolite by silver. Figure 16 shows one of these ores in which several areas of niccolite—dark gray with irregular borders—lie in a matrix of silver (light gray). In a few places the niccolite shows automorphic crystal outlines but most of its borders are so very irregular as to indicate at least a moderate amount of replacement by silver. Subsequent study of many more specimens from this and other mines at Cobalt and at South Lorraine have shown, however, that such replacements are very exceptional and that in most of the ores the simple arsenides are automorphic against silver and thus afford no evidence of having served as its precipitating agents.

ITHACA, N. Y.,
July 20, 1950.

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DISCUSSIONS

URANINITE IN THE COEUR D'ALENE DISTRICT, IDAHO.

Sir: There are some generalizations, descriptions, and statements used by Messrs. Ernest E. Thurlow and Robert J. Wright in their paper entitled "Uraninite In The Coeur d'Alene District, Idaho," [1] which I feel tend to lead to a misunderstanding of the geology of the Sunshine Mine and the occurrence here of uraninite. I believe that these deserve comment in order to keep the record straight.

The generalization which states that all the faults of the Silver Belt, with the exception of the Big Creek and Fort Wayne faults, are normal faults, is not wholly correct and is apt to be misleading insofar as it is not applicable to the Sunshine Mine. The Sunshine Mine is located on the western portion of the Silver Belt and contains the largest known silver-copper ore shoots of the area as well as the only known appreciable quantity of uranium mineralization in the district. Here, all the major faults in the mine workings, and the greatest majority of mappable faults are reverse type faults. Messrs. Thurlow and Wright took their information from Professional Paper No. 62 published in 1908,[2] and long before the Sunshine became even a moderate ore producer. Much more up-to-date data are available on the Silver Belt in the offices of the various mining companies.

Messrs. Thurlow and Wright also state that the known ore deposits in the Silver Belt occur in shear zones impinging upon the major faults with an angle of 20–30 degrees on strike. This infers that there are no known ore bodies in the shear zones parallel to the major faults. In the light of present available information, this is only partly true. It is applicable to the Sunshine vein system and some others. The greatest significant discoveries of ore made in the Coeur d'Alene District in the past ten years have been made at the Sunshine Mine where it has been proved that some of the major faults, and their parallel shear zones, are commercially mineralized. Indeed, two of our largest silver-lead ore shoots lie within such shear zones and the fault proper carries ore.

We fail to agree with Thurlow and Wright that the uraninite zones appear to intersect the Sunshine vein system. Good structural evidence exists which indicates that the reverse interpretation is most likely correct. Uraninite-bearing zones, with their accompanying halos of intense silicification and red jasper alteration, up to ten and fifteen feet in width, are definitely observed to be intersected by later major siderite-tetrahedrite veins. These veins contain

[1] Thurlow, Ernest E., and Wright, Robert J., Uraninite in the Coeur d'Alene District, Idaho: Econ. Geol., vol. 45, no. 5, pp. 395–404, 1950.

[2] Ransome, F. L., and Calkins, F. C., The geology and ore deposits of the Coeur d'Alene District, Idaho: U. S. Geol. Survey Prof. Paper 62, 1908.

no more than a trace of radioactivity as determinable by a standard Geiger-Mueller decimal scaler of the Atomic Energy Commission located in the chemical laboratory of the Sunshine Mining Company. This indicates to us that much of the uraninite is an early phase of the Sunshine mineralization epoch.

Messrs. Thurlow and Wright have also failed to note in the field and laboratory the presence of at least two generations of pyrite. A fine grained dark pyrite occurs as well as a coarse grained light pyrite. Megascopically at least, the uraninite occurs abundantly with the fine grained dark variety which is early and not with the coarse grained later type. It is thought that many of the other sulphides and oxides here are of multiple generations. We believe that research on the subject now being conducted will bring out a much more complex paragenesis than is set forth by Thurlow and Wright.

Lastly, it can be stated with confidence that almost ninety-eight percent of the assays made of uraninite veins and stringers in the mine show that a high uranium content is accompanied by a correspondingly high silver content. This is borne out by many samples taken for assay. On the other hand most of the rich silver shoots being mined do not contain any appreciable amount of uranium.

RAYMOND F. ROBINSON.

GEOLOGICAL OFFICE,
SUNSHINE MINING COMPANY,
KELLOGG, IDAHO,
Oct. 3, 1950.

REVIEWS

Geology and Ore Deposits of the La Plata District, Colorado. By EDWIN B. ECKEL, with sections by J. S. WILLIAMS, F. W. GALBRAITH, and others. Pp. 179; pls. 29; figs. 50. U. S. Geol. Survey Prof. Paper 219. Prepared in cooperation with the Colorado State Geological Survey Board and the Colorado Metal Mining Fund. U. S. Government Printing Office, Washington, D. C., 1949. Price, $2.50.

This report on the La Plata district is another restudy of a Colorado district by the Geological Survey. The area was earlier studied by the Hayden Survey and by the U. S. Geological Survey. The results of the latter published as the La Plata Folio, U. S. Geological Survey No. 60 by Whitman Cross, A. C. Spender, and C. W. Purington, 1899. It is interesting to note that the earlier report was prepared in 1896–97 and the folio published 1899. The field work of the later report was in progress 1935 to 1937. The report published 1949. The time between initiation of the work and publication of the earlier report was three years and in the present report 14 years. The war that occurred in the period of the earlier report was perhaps less distracting than the one that occurred in the interval of the later report.

The district is located in southwestern Colorado in the area between the Colorado plateau and the San Juan Mountain uplift. The La Plata district and the Rico district to the north appear intermediate in character between the San Juan mountain uplift to the east with its lava fields and centers of intrusion and the more definitely laccolithic mountains of the Colorado plateau to the west, as the Carrizo Mts. of Arizona and the Abajo, La Selle and Henry Mountains of Utah. Physiographically the area has the same general history as the neighboring San Juan area, with less vigorous igneous activity. There is no evidence that lavas ever flowed out on the surface as happened in two periods, in the San Juan mountain area.

The La Plata mountains were carved by erosion from a domal uplift resulting from the injection of igneous material into a thick series of relatively incompetent sedimentary rocks. As in the San Juan area there was more than one period of uplift and subsequent erosion. The sedimentary rocks exposed in the district are shown in the following table.

The formations shown in the table are presumably underlain by earlier Paleozoic formations as well as Precambrian rocks and were once overlain by Cretaceous and Tertiary sedimentary rocks that have been eroded.

The igneous rocks are all intrusive and in general of intermediate composition. They are classified on the basis of texture as porphyritic and non-porphyritic. The porphyritic rocks are earlier and form the sills, laccoliths and some stocks. They were probably injected and their bulk added to that of the sedimentary rocks, resulting in the doming of the sedimentary rocks. There was little metamorphism of the sedimentary rocks during this period.

The non-porphyritic rocks are thought to have, in large part, replaced or assimi-

SEDIMENTARY ROCKS OF THE LA PLATA DISTRICT.

Age	Formation	Member	Thickness (feet)
Upper Cretaceous	Mancos shale		1,200
	Dakota (?) sandstone		100–150
Upper Jurassic	Morrison formation	Shale	400–625
	Junction Creek sandstone		160–500
	Wanakah formation	Marl and Bilk Creek sandstone	25–125
		Pony Express limestone	0–25
	Entrada sandstone		100–265
Jurassic (?) and Upper Triassic	Dolores formation		500–750
Permian	Cutler formation		1,500–2,200
	Rico formation		100–300
Pennsylvanian	Hermosa formation		2,750

lated the country rock. The field relations that support this idea are clearly and effectively set forth and discussed. To those who are favorably disposed to assimilation and replacement and have seen the intense alteration in the central portion of the district, this may be sufficient but both those who favor assimilation and those who question it would have appreciated a more complete presentation of the mineralogical and chemical changes accompanying this interesting phase of the geology. An author, however, must decide on the features of a district that seem to most deserve emphasis.

Metamorphism of the sedimentary rocks is largely associated with the later non-porphyritic intrusions.

The outstanding structure is an elliptical dome on the southwesterly dipping flank of the greater San Juan uplift. A feature of the domal uplift is a horseshoe shaped hinge fold open at the south that nearly encircles the central portion of the mountains. The opening to the south is crossed by steep faults with down-throw outward from the dome. The result of the hinge fold is a rather sharp drop from the flat top to the gently dipping outward slopes of the dome.

The first definitely known mineral discovery was in 1873 and for the following quarter century many locations were made but with little production. Most of the production with a value of approximately $6,000,000 was subsequent to 1900. By far the greatest value has been in gold though more than 2,000,000 ounces of silver have been produced and small amounts of base metals.

In the section on mineralogy Galbraith describes 65 mineral species. Of special interest are the tellurides which are described and figured in detail. The paragenetic sequence of vein minerals is effectively shown diagrammatically. It is interesting to note that sulfur minerals as sulfate (barite) and as sulfide (pyrite) are shown as essentially contemporaneous early vein minerals. Also of interest is the occurrence of roscoelite (vanadium mica) as a widespread, and locally at least abundant,

associate of telluride ores. Vanadium ores of the sandstone type are not reported in the district.

The following table gives the classification of the ore deposits.

1. Disseminated chalcopyrite with platinum and palladium
2. Gold with sulfides:
    a. Contact metamorphic replacement bodies
    b. Gold-bearing pyrite:
        Veins
        Replacement bodies
        Breccia bodies
    c. Mixed sulfides with silver and free gold
3. Chalcocite veins
4. Ruby silver veins
5. Telluride deposits:
    a. Veins
    b. Replacement bodies
6. Gold placers

This classification arranges the deposits in the general order of temperature of formation and also is a broad zonal arrangement. Only the higher temperature deposits occur within the horseshoe shaped hinge-fold or the area of most intense metamorphism. Most of the productive mines are in or close to the hinge-fold zone that surrounds the central portion of the district. The telluride deposits have been by far the most productive, and the most productive of those are associated structurally with faults that cross the open end of the horseshoe fold.

A type of copper deposit in the northern part of the district on Bear Creek has been described by E. N. Goddard. These have characteristics of the "Red Bed" copper deposits. They are confined stratigraphically to the lower part of the Dolores formation which has been bleached from red to gray where mineralized. Chalcocite is the primary copper mineral. The deposits are intimately associated with dikes and are regarded by Goddard as of hydrothermal origin.

Ore shoots of the La Plata district are controlled by both structure and the type of country rock. Brittle rocks of whatever composition and whether original or induced brittleness have been favorable to shattering along fractures and therefore favorable to movement of ore solutions and to mineralization. Change in dip and in strike of fissures has influenced the degree of permeability along fissures and consequently of the formation of ore shoots. Limestone has been favorable both physically and chemically to replacement deposits.

Usually at least two favorable conditions are essential to the production of an ore shoot. Plate 6 of the report gives an effective diagrammatic picture of the different conditions that have produced ore shoots.

Weathering and oxidation of the deposits has been widespread but as elsewhere in the high Rocky Mountains glaciation has scoured off much of the weathered portion on the higher areas. However, some of the pyritic deposits have been rendered commercial by oxidation.

Gold placers are widespread in streams originating in the La Plata mountains. Glaciation has, however, swept the original placers out of the higher valleys and the production from placers has been small.

The primary ore deposits are regarded as formed by hydrothermal solutions given off following the emplacement of the later or non-porphyritic intrusive rocks.

As in numerous recent reports "clay minerals" are recognized as rather abundant as hydrothermal alteration products which leads the author to speculate on the possibility or probability of acid hydrothermal solutions. The telluride deposits have a known vertical range of 4,500 feet with 5,000 to 9,000 feet of sedimentary rocks eroded after deposition of the ores.

Probable deposition at a depth of 10,000 to 15,000 feet has led the author to hesitate to place the telluride deposits definitely in the epithermal group of deposits.

The future of the district appears not too bright though the author states that "future production may well equal if not exceed that of the past."

The future apparently depends on the discovery of high grade deposits similar to those that have been most productive in the past and on the possibility of profitably mining and treating some of the pyritic gold ores below the zone of enriched oxidized ores.

A project, long considered in the district, is the prospecting of limestone beds in the Hermosa formation that have been largely productive in the Rico district to the north. The report shows that the beds that have been most productive in the Rico district, if present in the La Plata area, are several hundred feet at least below the present surface where erosion cuts deepest into the sedimentary rocks. This would seem a situation to justify some drilling by the U. S. Geological Survey for geological information that might well contribute to the solution of the problem.

This excellent report contributes an important unit to the larger problem of the geology of the laccolithic mountains and their relation to the neighboring San Juan mountains and the relation of the ore deposits of these outlying igneous centers to the deposits in the sedimentary rocks of the plateau area. It is to be hoped that the Geological Survey may find it possible to bring all these features together in a comprehensive report that will be of large scientific interest and possibly no little economic importance.

The study, by the Geological Survey, of districts of lesser production is fully justified, both for the help it will be to future development and the contribution that it makes to the science of ore deposits.

B. S. BUTLER.

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TUCSON, ARIZONA,
Sept. 1, 1950.

Geology and Mineral Deposits of the Cartersville District, Georgia. By THOMAS L. KESLER. Pp. 97; pls. 19; figs. 14. U. S. Geol. Survey Prof. Paper 224. U. S. Government Printing Office, Washington, D. C., 1950. Price, $1.75.

The Cartersville mining district in northwest Georgia is one of the oldest in the United States and has been continually active for more than 100 years. Large amounts of brown iron, ocher, and manganese have been produced, and Cartersville has furnished roughly a quarter of the barite produced in the United States. The district differs from the "typical" mining district in that virtually all ore has been produced from residual materials, and in general the valuable minerals have been concentrated by washing them out of the clay residual from dolomite.

The U. S. Geological Survey has now published a full report on the Cartersville district prepared by Thomas L. Kesler, who has studied the district for more than a decade. The report covers all aspects of the geology, though instead of describing every mine opening (of which 149 are listed as having been appreciably productive in an area 1 to 5 miles wide and 18 miles long), 27 representative mines or

groups of mines are discussed in some detail. Although a deep mantle of residual, colluvial, and alluvial material covers most of the area, through which the mines have rarely penetrated, Kesler has painstakingly accumulated a remarkable amount of detailed areal, structural, and petrologic information concerning the bedrock, much of it by close attention to the residuum itself, and he has also studied the mantle materials for their own contribution to the geologic history.

It may be this deep and frustrating mantle that has led Kesler into his healthy but perhaps somewhat extreme skepticism concerning older views on faulting and metamorphism in the area, which bursts out occasionally in his discussion of previous workers (e.g., pp. 30–33). Few would deny that many faults have been postulated in the southern Appalachians on entirely insufficient evidence, but on the other hand many major faults demanded by the areal distribution of clearly defined formations cannot anywhere be found exposed in mine cuts or roadside exposure. In at least two cases known to the reviewer invisible faults drawn only on such grounds have later been spectacularly verified by drilling or excavation.

One of the most interesting problems raised by Kesler is that of the structural control of the ore deposits, or rather of the parent materials from which the actual ores were produced by weathering. Kesler has demonstrated that in the center of the district strikes and fold axes trace out a pronounced sigmoid curve and that the pattern of faults in that area is remarkably in accord with theoretical expectations. His Figure 3 (p. 28), comparing the fault pattern close to Cartersville with the results of Mead's experiments (Jour Geology, vol. 28, pp. 518–528, 1920), will be of great interest to structural geologists. Curiously he has not mentioned that the area covered by this figure corresponds precisely with the belt of barite mines in the district, from which nearly 2 million short tons of barite has been removed, though this coincidence would seem to put the capstone on his proof of structural control of ore. To the reviewer, his argument for structural control of manganese deposits is much less convincing, for the manganese (and brown iron) mines show no limitation to the area of the sigmoid curve but are scattered along the full length of the outcrop belt of the host formation.

It is unfortunate that a report containing so much valuable information should show certain purely editorial lapses not ordinarily expected in reports of the U. S. Geological Survey. The index is quite inadequate, being little more than an alphabetical listing of center headings. The large number of mines referred to throughout the text can only be identified by constant cross-reference from the map to an inside page of the report, and at least one pair of unrelated mines some distance apart are given the same name and seldom properly distinguished. If the map number of the mine could have been inserted in parentheses in the text at each reference, the report would have been little more bulky or difficult to prepare and the reader unfamiliar with the area would have been greatly aided.

JOHN RODGERS.

YALE UNIVERSITY,
NEW HAVEN, CONN.,
September 7, 1950.

Geology for Engineers. By JOSEPH M. TREFETHEN. Pp. 620; numerous figures and photographs; colored topographic maps; tbls. 27. D. Van Nostrand Co., Inc., New York, 1949. Price, $5.75.

Professor Trefethen has written a lucid, well-illustrated geologic textbook designed to be used for an introductory geology course for sophomore or junior engi-

neering students. This book is intended to provide the knowledge of geology which would be necessary for a civil engineer. The practical application of basic geologic principles to engineering is particularly stressed in the chapters on Subsurface Water, Earth Movements, Earthquakes, Streams, Dam Sites and Reservoirs, Soil Erosion, and Shorelines.

The emphasis in this book is on engineering geology, and therefore the author has summarized or eliminated entirely the non-engineering aspects of geology. The book contains one short chapter on Earth History and practically nothing pertaining to economic geology. The author has designed this book for the use of a particular audience and has accomplished his purpose.

The book has practical chapters on Geologic Mapping and Geological Field Work. The chapter on the Geologic Interpretation of Topographic Maps and Airplane Photographs contains thirteen well-chosen colored plates selected from topographic maps which illustrate particular geologic features. Numerous aerial photographs are also included.

The book is excellently illustrated with photographs and diagrammatic line drawings. Several of the photographs, however, lack captions. The line drawings are simply constructed and are easily interpreted because extraneous details have been omitted. The book is peppered with tables and occasional formulae which serve as a constant reminder to the reader of the trend toward the quantitative approach in geology. The three appendices include ten tables which summarize the physical properties of various rock types.

SPENCER S. SHANNON, JR.

The Geology of the Commonwealth of Australia. By T. W. EDGEWORTH DAVID; edited and supplemented by W. R. BROWNE. Pp. 1, 365; figs. 372; pls. 85; tbls. 35; 2 colored maps. Edward Arnold & Co., London, and Longmans, Green and Co., New York, 1950. Price, 12£ 12s ($50.00).

This great monographic work appears in two volumes of text and one large volume of colored geological maps. The idea of it was conceived by Sir Edgeworth David just after World War I as a one volume work and he actively embarked upon it upon his retirement as Professor of Geology from the University of Sydney in 1924. The first fruits appeared in 1932 as a large colored map of the geology of Australia with a volume of Explanatory Notes, which constituted a summary of Australian geology known at that time. This map is included in Volume 3.

Sir Edgeworth David realized that the task of compiling such a comprehensive work was beyond the abilities of one man and he enlisted the help of many colleagues. At the time of his death in 1934 the book was still unfinished and desirous of perpetuating the memory of one of Australia's great scholars, the Government of New South Wales purchased the manuscript and arranged for its completion and publication under the direction of Dr. Browne, who had been helping Sir Edgeworth David with the manuscript. He was commissioned to revise the text, and complete the volume as nearly as possible according to the original design. In this he was assisted by most of the geologists of Australia and several from other countries. The contributors are so numerous that two and one half pages of the preface are used for acknowledgments. Publication was prevented by World War II, when a further revision was undertaken to prepare it for publication.

An idea of the scope and arrangement may be gained from a glance at the table of contents. Volume I is made up of Part I, Historical Geology, of 720 pages. Its 15 chapters deal with a systematic treatment of the geology, geologic period by

period, as represented in Australia, with one chapter on Australian New Guinea, and another on Tectonic History. The comprehensive text matter is illustrated by 57 plates and 208 text-figures depicting distribution of formations, cross sections, tectonic features, and plates of fossils and geologic features. Under each geologic period are considered the stratigraphy, paleontology, igneous and metamorphic rocks, and economic geology of the various political divisions, followed by an extensive bibliography.

The Australian aboriginal man is considered to have arrived from Asia in late Pleistocene, probably via a land bridge through New Guinea, and Tasmanian aboriginal man perhaps in early Pleistocene.

Volume 2 contains Part II, Physiography (127 pages), and Part III, Economic Geology (450 pages). Part II covers the detailed geomorphology, state by state, with concluding chapters on "Physiographic History," and on "Soils," the last being very interesting to American readers.

Part III has the following chapter headings: Distribution of Ores in Space and Time; Gold, Silver, Lead, Zinc, Cadmium, Iron, Manganese and Copper; Tin, Tantalum, Molybdenum, Tungsten, Antimony, Arsenic, Bismuth, Titanium, Zirconium, Uranium, Radium, and other Rare Elements; Nickel, Cobalt, Chromium, Mercury, Platinum, and Platinoid Metals; Fluorspar, Quartz, Felspar and Chinastone, Barytes, Sulphur Minerals, Mica, Vermiculite, Asbestos, Talc and Soapstone, Graphite, Sillimanite, Andalusite and Cyanite, Corundum, and Emery; Limestone, Dolomite, Phosphates, Siliceous Material, Diatomaceous Earth, Magnesite, Laterite and Bauxite, Alunite, Clays, Bentonite, Ochres and Oxides, Vanadium Minerals, Gypsum and Salt; Building and Ornamental Stones, Gemstones; Coal (3 chapters); Oil-shales; Petroleum and Natural Gas; Artesian Water; Groundwater. The largest chapters deal with gold, coal, artesian water and nonmetallic minerals. The various deposits in each state are described in considerable detail and are shown by many fine illustrations. This part is a compendium of information of all the many mineral deposits of the continent.

Volume III carries the Geological Map of the Commonwealth of Australia, with eleven sections, in 4 sheets; and a Geological Sketch-Map of Australian New Guinea, with one section.

The three volumes represent fine cooperative effort on the part of many geologists, organizations, and mining and oil companies, who have contributed their effort, knowledge, and time, to bringing together the known geological information of Australia. It is a fine tribute to a great geologist.

ALAN M. BATEMAN.

Petroleum Production Engineering: Petroleum Production Economics. By LESTER CHARLES UREN. Pp. 639; figs. 117; tbls. 74. McGraw-Hill Book Co., Inc., New York, 1950. Price, $7.50.

This third volume of the author's Petroleum Production Engineering series deals with the economic aspects of the industry and supplements "Oil Field Development," 3rd Edit., 1946, and "Oil Field Exploitation," 1939. This volume presents an elementary exposition of the basic principles of economics and business administration as applied to petroleum production. It is designed to be of value to the practical engineer as may be seen from the following chapter headings: Economic Structure of the Petroleum and Natural-gas Industry; Geographic Distribution of Petroleum; Oil- and Gas-land acquisition and Control; Industrial Organization for Oil and Gas Production; Oil-industry Finance; Labor Management in the Petroleum-

producing Industry; Materials and Equipment Used in the Petroleum-producing Industry; Petroleum-Industry Taxation; Cost Accounting for Petroleum Production; Engineering Problems in Economic Exploitation of Oil-producing Properties; Appraisal of Oil- and Gas-producing Properties; Conservation of Oil and Gas Resources.

The chapter headings alone do not convey all of the information that is packed into them. Under Chapter 1, for example, is included in addition to the economic structure data on exploration, reserves, geologic age, drilling, transportation, refining, carbon black, consumption, markets, storage, and other features. A selected bibliography follows each chapter, and numerous charts and records supply additional information.

The book is well written and nicely printed and should prove of great value to all of those interested in the petroleum industry.

BOOKS RECEIVED.

CHARLES H. SMITH.

Mineral Commodities of California. Under direction of OLAF P. JENKINS. Pp. 443; pls. 17; figs. 34; 1 map. California Div. Mines Bull. 156, San Francisco, August 1950. Price, $2.00. *Geologic occurrence, economic development, and utilization of California's mineral resources. Over 80 different kinds of raw minerals described. Bulletin is divided into 5 parts; 1, summary of mineral wealth of California, for 1948; 2, mineral fuels; 3, industrial minerals; 4, metals; 5, directory of mineral producers, dealers and commercial laboratories. An invaluable reference book.*

California Fossils for the Field Geologist. HUBERT G. SCHENCK AND A. MYRA KEEN. Pp. 88; pls. 56. Stanford Univ. Press, Stanford, Calif., 1950. *A pictorial fossil guide with extensive bibliography.*

Oil and Gas Developments in Kansas During 1949. W. A. VER WIEBE, J. M. JEWETT, E. K. NIXON, R. K. SMITH, AND A. L. HORNBAKER. Pp. 175; figs. 31; tbls. 44. Kansas Univ. Pub., Bull. 87, 1950.

Rate of Depletion of Water-Bearing Sands. FREDERIC HARTWELL KELLOGG. Pp. 15; figs. 2. Mississippi Geol. Survey Bull. 70, University, 1950. *A theoretical discussion of methods of estimating rates of depletion. Concludes that methods based on analysis of unsteady state flow rest on a fallacious premise. Entire method of attack should be changed to an analysis of two-phase steady state flow.*

Pennsylvania Topographic and Geologic Survey—Harrisburg, 1949–1950.

Bull. G-23. Pleistocene Terraces of the Susquehanna River, Pennsylvania. LOUIS C. PELTIER. Pp. 158; figs. 49; tbls. 46. *A detailed description directed toward establishment of a Pleistocene chronology for central Pennsylvania and the determination of the climatic fluctuations which occurred during that period.*

Bull. G-25. Subsurface Projection of Cambro-Ordovician Sediments in the Pennsylvania-New York Region. FRANK M. SWARTZ. Pp. 18; figs. 16. *Includes preliminary estimates of oil and gas possibilities in Cambro-Ordovician sediments.*

Bull. M-29. McDonald and Adjacent Oil Fields, Allegheny and Washington Counties, Pennsylvania. A. I. INGHAM, E. M. TIGNOR, AND W. M. NABORS. Pp. 113; figs. 14; pls. 10; tbls. 4. *2 parts; 1, geology; 2, secondary recovery of oil.*

Bull. M-30. East Fork-Wharton Gas Field, Potter County, Pennsylvania. JOHN R. EBRIGHT, CHAS. R. FETTKE, AND ALBERT I. INGHAM. Pp. 43; figs. 2; pl. 1. *Description of topography, stratigraphy, structure, and well records.*

Bull. M-31. Summarized Record of Deep Wells in Pennsylvania. CHAS. R. FETTKE. Pp. 148; pls. 2; figs. 2; tbls. 6.

Bull. M-33. Water Flooding in Pennsylvania. CHAS. R. FETTKE. Pp. 30; figs. 17; tbls. 3. *An account of the artificial water flooding method of producing oil in Pennsylvania. In 1946 about 80% of oil produced was obtained by this method.*

Bull. W-8. Ground-Water Resources of the Valley-Fill Deposits of Allegheny County, Pennsylvania. J. H. ADAMSON, JR., J. B. GRAHAM, AND N. H. KLEIN. Pp. 181; pls. 5; figs. 9; tbls. 3.

Progress Rept. 133. Gas in Leidy Township, Clinton County, Pennsylvania. S. H. CATHCART. Pp. 15; pl. 1; figs. 3.

Ball Clay of the Troup District, Texas. H. B. STENZEL. **Characteristics of Texas Ball Clay near Troup.** F. K. PENCE. Pp. 54; figs. 23; pls. 9; 1 map. Bur. Econ. Geol., Texas Univ. Pub. 5019, Austin, 1950. *Presents data on occurrence, extent, and stratigraphic position of ball clay deposits as well as chemical analyses and other technical data relating to them.*

Canada Department of Mines and Technical Surveys—Ottawa, 1950.

Mem. 253. Fiedmont Map-Area, Abitibi County, Quebec. L. P. TREMBLAY. Pp. 113; figs. 11; pls. 5; 1 map. Price, 75 cts. *Describes geology and mineral deposits of an area underlain by nearly equal amounts of early volcanic rocks and later Precambrian intrusions.*

Mem. 254. Alexo and Saunders Map-Areas, Alberta. O. A. ERDMAN. Pp. 100; pls. 6; figs. 5; maps 2. Price, $1.00. *In Foothills belt of west-central Alberta. Concerned especially with structural geology and describes well exposed folded faults in rocks of both Paleozoic and Mesozoic ages.*

Bull. 16. The Groundhog Coalfields, British Columbia. A. F. BUCKHAM AND B. A. LATOUR. Pp. 82; figs. 5; pl. 1; 1 map. Price, 75 cts. *Upper Jurassic or Lower Cretaceous coal of anthracite grade in a difficultly accessible area of northern British Columbia. Large amounts indicated, but seams are jointed, crushed, and dirty.*

Ontario Department of Mines—Toronto, 1950.

P. R. 1950-6. Preliminary Report on the Geology Along the Mississagi Road. W. D. HARDING. Pp. 4; 1 map. *From Twp. 1-F to Chapleau. Largely Algoman granitic rocks. Some radioactive minerals.*

P. R. 1950-7. Preliminary Report on O'Sullivan Lake Area. W. W. MOORHOUSE. Pp. 5; 1 map, scale 1″ = ½ mi. *General, structural, and economic geology outlined.*

58th Annual Report, Vol. LVIII, Pt. II, 1949. Mines of Ontario in 1948. I. WILLIAMS. Pp. 111. *Statistics.*

Quebec Department of Mines—Quebec, 1949–1950.

List of the Principal Operators and Owners of Mines and Quarries in the Province of Quebec. Pp. 90. *Names, addresses, and mine locations listed.*

The Mining Industry of the Province of Quebec in 1948. Pp. 88; tbls. 41. *Account of mining operations and statistical data for 1948.*

Geol. Rept. 43. North Shore of the Saint-Lawrence from Aguanish to Washicoutai Bay, Saguenay County. JACQUES CLAVEAU. Pp. 40; pls. 14; 1 map. *Early Precambrian gneisses and intrusives. Some fluorite of interest associated with granites.*

Leitfaden für die Exakte Edelsteinbestimmung. K. SCHLOSSMACHER. Pp. 174; figs. 21; pls. 3; tbls. 8. E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, 1950. Price, DM 13.60. *A simply written manual for the accurate determination of precious stones. Optical properties and methods are emphasized. Sections on specific weight and hardness, descriptions of stones and determinative tables included.*

Die Eigenschaften der Minerale, I. ARNO SCHÜLLER. Pp. 174; figs. 11; numerous tables. Akademie-Verlag, Berlin, 1950. *The properties of minerals. Part I, the external distinguishing properties, particularly of the ore and rock forming minerals. After a brief description of mineral properties, a determinative table including 450 minerals is given, subdivided on the basis of lustre and hardness.*

Annales du Service des Mines, Tome XV. Under direction of M. E. REINTJENS. Pp. 76; figs. 24. Comité Spécial du Katanga, Bruxelles, 1950. Price, 100 fr. *A mineralogical description of the minerals of the Heterogenite group (hydrated cobalt oxides), with a discussion of their origin from sphaerocobaltite.*

Brazil Departamento Nacional da Produção Mineral—Rio de Janeiro, 1949.

Bol. 128. A Faixa Costeira de Vitória. ALBERTO RIBEIRO LAMEGO. Pp. 68; figs. 50; 1 map. *Geology of the coastal region near Vitória with descriptions of mineral occurrences.*

Bol. 129. Contribuição ao Estudo do Devoniano Paranaense. SETEMBRINO PETRI. Pp. 125; figs. 10; photos 5; 1 map. *Stratigraphic and paleontologic studies of the Devonian of the State of Paraná.*

Bol. 130. Jazimentos de Minerais Metalíferos no Brasil. EVALDO OSÓRIO FERREIRA. Pp. 122. *Brief descriptions of metallic mineral occurrences, with extensive bibliographies.*

Bol. 131. Bibliografia e Indice da Geologia do Brasil, 1943–1944. DOLORES IGLESIAS AND MARIA DE LOURDES MENEGHEZZI. Pp. 62. *Bibliography of Brazilian geology.*

Nota Prel. 48. A Série Tubarão na Bacia do Rio Tietê, Estado de São Paulo. OCTAVIO BARBOSA AND FERNANDO F. M. DE ALMEIDA. Pp. 16; tbl. 1; 1 map. *Deals with Permian glacial beds in State of São Paulo.*

Nota Prel. 49. Novas Observações sôbre a Paleontologia e Geologia do Depósito Calcáreo de São José de Itaboraí. CARLOS DE PAULA COUTO. Pp. 13; figs. 7. *New observations on the paleontology and geology of a limestone deposit at São José de Itaboraí, in the State of Rio de Janeiro.*

A Jazida de Djalmaíta, de Volta Grande Rio das Mortes, Minas Gerais. DJALMA GUIMARÃES. Pp. 20; figs. 4; tbls. 7. Acad. Ciencias Brasileira, Rio de Janeiro, 1950. *Description of djalmaite occurring with cassiterite, tantalite, and spodumene in pegmatite at Volta Grande, Rio das Mortes, Minas Gerais.*

SOCIETY OF ECONOMIC GEOLOGISTS

The Coal Geology Committee, Society of Economic Geologists, held a round-table discussion of Permo-Pennsylvanian Stratigraphic Problems, on Friday, November 17, 1950, at the Washington Meeting of the Geological Society of America.

Co-chairmen: Paul H. Price, West Virginia Geological Survey, Morgantown, W. Va., and John H. Melvin, Ohio Geological Survey, Columbus, Ohio.

Discussion Leader: Monroe G. Cheney, Anzac Oil Company, Coleman, Texas.

OBJECTIVES.

To review problems related to detailed stratigraphic study of Upper Pennsylvanian and Permian strata of the Dunkard Basin of Ohio, West Virginia and Pennsylvania, and to discuss certain principles embodied as they are involved in regional studies.

PROGRAM.

1. Resumé of the nature and results of the Special Field Conference, Sept. 8–10, 1950, on the Upper Pennsylvanian and Lower Permian Strata of the northern portion of the Dunkard Basin, and summary of recommendations.—Aureal T. Cross, Conference Leader, West Virginia Geological Survey and University, Morgantown. (10 min.)
2. A revised outline of the stratigraphy of the northern portion of the Dunkard Basin. Aureal T. Cross. (10 min.)
3. Selected topics discussed:—Introduction. Monroe G. Cheney.
   - A.—Significance and usefulness of cyclothems.
     Initial discussant: Harold R. Wanless, Univ. of Illinois, Urbana.
   - B.—Explanation of origin of cyclothems.
     Initial discussant: Wm. C. Krumbein, Northwestern Univ., Evanston, Ill.
   - C.—Stratigraphic boundaries and problems in their selection.
     Initial discussant: Carl O. Dunbar, Yale Univ., New Haven, Conn.
   - D.—Rank of individual beds, cyclothems and larger stratigraphic groups.
     Initial discussant: Lewis M. Cline, Univ. of Wisconsin, Madison.
   - E.—Nomenclature of cyclical sedimentary sequences.
     Initial discussant: Raymond C. Moore, Kansas Geol. Survey.
4. Business Meeting, Coal Geology Committee, S.E.G., Gilbert H. Cady, Chairman.

The round-table meeting was a follow-up of the discussions which were held in connection with the Special Field Conference on Stratigraphy, Sedimentation and Nomenclature of the Upper Pennsylvanian and Lower Permian Strata in the Northern Portion of the Dunkard Basin, September 8–10, 1950.

A brief resumé of the nature of that conference and the opinions and recommendations made by the participants on the several problems introduced there was made at the opening of the Round-table Discussion by the conference leader, Aureal T. Cross.

As a result of those deliberations at the Field Conference the "Selected topics discussed" (3A-E on preceding page) were selected as being of broad general interest to those working with strata of this age and of particular pertinence to the questions raised in September by the participants of the Conference.

A prepared statement of opinion or recommendation of these points was formulated by Dr. Cross, and sent to a number of persons known to be interested in such studies in advance of the meetings in Washington.

The discussion leaders presented each topic for discussion and the initial discussant gave a brief statement of his position regarding the problem. This brought forth immediate discussion from the floor which was guided by the discussion leader.

The entire Round-table Discussion was recorded and either a summary of opinion, recommendations, and agreement reached or a record of the entire proceedings was circulated later to those in attendance.

SCIENTIFIC NOTES AND NEWS

OLIVER BOWLES, who retired from the U. S. Bureau of Mines in 1947, is again on the staff in the capacity of a consultant dealing with special phases of strategic minerals.

M. W. JASPER is now a mining engineer and geologist for Western Uranium Cobalt Mines, Ltd., S. Hazelton, B. C.

S. G. LASKY of the U. S. Geological Survey is one of six civilians from the civilian agencies of the government who have been detailed to attend the Industrial College of the Armed Forces for the current academic year.

WILLIAM W. LYNCH, mining engineer, was elected vice-president of the Calumet & Hecla Consolidated Copper Co. He was New York representative of the firm.

STUART ST. CLAIR left in August for an extended trip in the East Indies, where he has been engaged in mineral and mine examination work.

OTTO C. VON SCHLICHTEN, of the Geological and Mineralogical Department of the University of Cincinnati, died October 4 of a heart attack. He was 64. Surviving are his widow, Mrs. Anna Erlwein von Schlichten; a daughter, Margaret Marie, living in California; and a son, Captain Harold C., of the Air Force.

The Departments of Mineralogy and Geology at Queen's University, Kingston, Ontario, have been amalgamated into a single Department of Geological Sciences. Professor J. E. Hawley, for 21 years head of the Department of Mineralogy, has been appointed Miller Memorial Research Professor to succeed the late E. L. Bruce, and is also acting as chairman of the new department for 1950–51. Dr. A. W. Jolliffe, formerly of McGill University, has joined the new department as Professor of Geology and is giving courses in both mineralogy and geology. Specialization will be continued in Precambrian, structural, and economic geology and in various phases of mineralogy. Courses in Sedimentation and Sedimentary Petrography have been inaugurated and a revised course in engineering geology will be offered to all geology students as well as civil engineers. Other members of the department include Professor Bruce Rose, W. J. Ambrose, L. G. Berry, and R. D. MacDonald.

Representatives of the U. S. Atomic Energy Commission and the Government of the United Kingdom have held conferences in Johannesburg, South Africa, with Union authorities in regard to the production of uranium from South African gold-bearing ores. The discussions were a continuation of those which took place in the Union in November last year. Representing the U. S. were: Mr. Jesse C. Johnson, Manager, Raw Materials Operations, U. S. Atomic Energy Commission; Mr. Frank McQuiston, special advisor to Mr. Johnson, and Mr. A. A. Wells, special assistant to the AEC General Counsel.

The American Association of Petroleum Geologists, the Society of Economic Paleontologists and Mineralogists, and the Society of Exploration Geophysicists

will hold a joint annual meeting of the three petroleum exploratory societies at the Jefferson Hotel, St. Louis, Missouri, on April 23 to 26, 1951.

B. S. W. Buffam, A. S. Dadson, H. C. Gunning, Christopher Riley, W. H. Callahan, and T. S. Lovering, members of the Society of Economic Geologists, were recent visitors to Giant Yellowknife Gold Mines at Yellowknife, Great Slave Lake, N. W. T., Canada.

F. G. FORMAN has commenced practice as a Consulting Geologist within Australia or Overseas with office at 15 Congdon Street, Claremont, Western Australia.

ALAN T. BRODERICK has left the employ of the Bunker Hill & Sullivan Co., Kellogg, Idaho, and is now regional geologist with the M. A. Hanna Co. at Iron River, Mich.

A. F. BANFIELD, associate geologist of Behre Dolbrear & Co., New York, returned after spending the season directing exploration and mapping in the Yellowknife area.

JOHN H. ERIC, geologist with the U. S. Geological Survey, was transferred from the San Francisco office to the Washington, D. C., office.

CHARLES F. JOY is now resident geologist and engineer for the Anaconda Copper Shoshone mines division, Tecopa, Calif.

E. P. LANGE returned from Saudi Arabia last September. He was employed as mining engineer by the Saudi Government Bureau of Mines for the purpose of developing nonmetallic mineral deposits.

EMMONS MEMORIAL FELLOWSHIP

The S. F. Emmons Memorial Fellowship in Economic Geology is available for the academic year 1951–1952, with a stipend of $1,200.00. Applications and accompanying testimonials should be submitted not later than March 1, 1951. Applicants should be qualified by training and experience to investigate some problems in Economic Geology and should submit a definite statement of the problem to the Committee, under whose oversight the work may be undertaken at any institution approved by them. The Fellow must give entire time to the problem, which may be used for a doctorate dissertation. Application blanks may be obtained from Alan M. Bateman, Yale University, H. E. McKinstry, Harvard University, Paul F. Kerr, Columbia University, or the Secretary, Columbia University.

MINING GEOLOGISTS NEEDED

The U. S. Geological Survey's new responsibilities under the Defense Production Act of 1950 will require the addition of mining geologists for field and office work on metallic and nonmetallic mineral deposits. Field work will consist of making mine examinations and appraisals in connection with applications for loans, purchase contracts, and other encouragement under the Act. Office work will be done in Washington, D. C., and will consist largely of reviewing and analyzing field appraisals and other data, and making recommendations in cooperation with the Bureau of Mines, Defense Minerals Administration, and other agencies for expansion of mineral production. Openings are available at grades of GS-9 ($4600 per year) to GS-13 ($7600 per year). A minimum of 5 years post-bachelor experience, preferably in mining geology, is required for these positions. For further information write to the Chief, Mineral Deposits Branch, U. S. Geological Survey, Washington 25, D. C.

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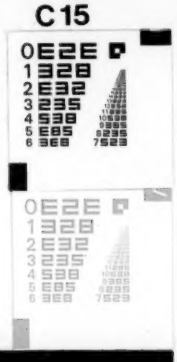
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